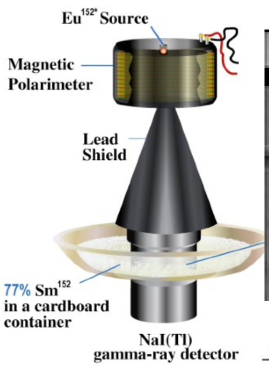
New Results of Electron Antineutrino Disappearance From the Daya Bay Experiment

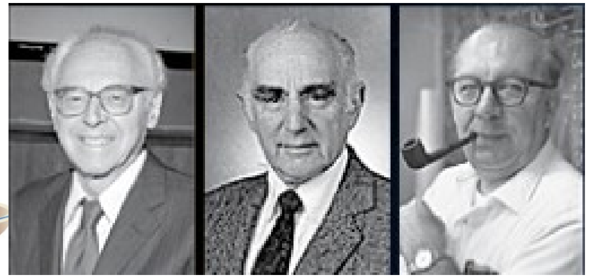
Jiajie Ling (BNL)
On behalf of the Daya Bay Collaboration

BNL Seminar
Aug 23, 2013

BNL ν History

>50 years





M.Goldhaber L.Grodzin A.W.Sunyar

Neutrinos are all left-handed

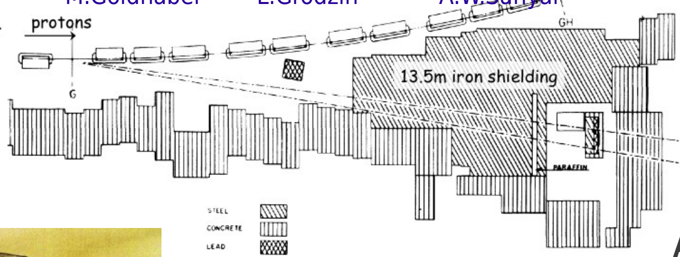


FIG. 1. Plan view of AGS neutrino experiment.

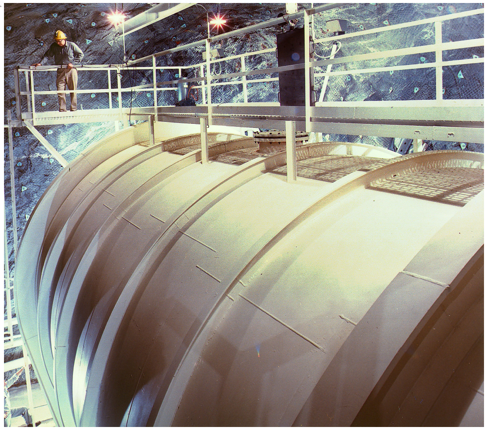
AGS

Muon neutrino discovery

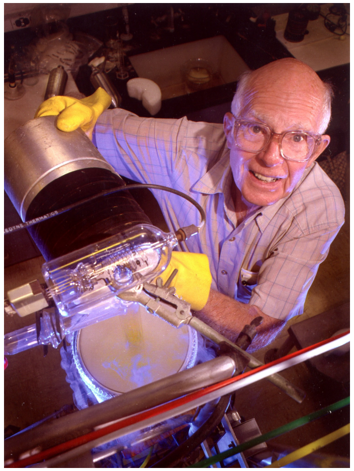
Leon M. Lederman Melvin Schwartz Jack Steinberger

Nobel Prizes

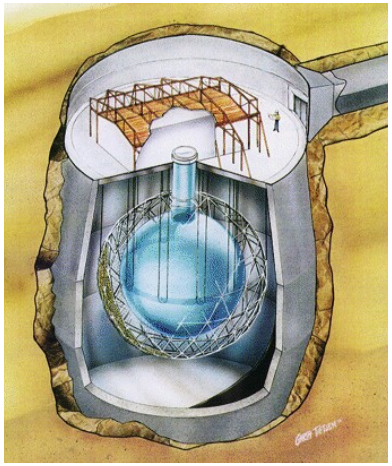
Solar neutrino missing puzzle



Homestake



Raymond Davis Jr.



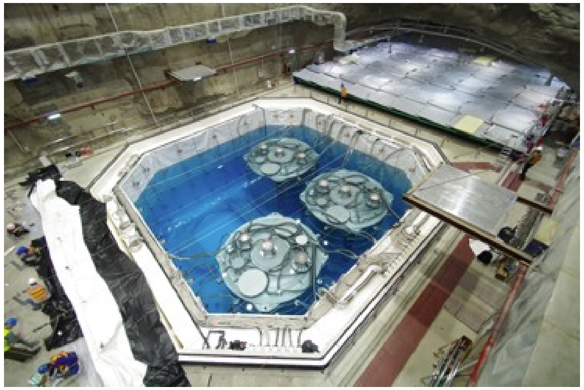
SNO

Solar neutrino oscillation

MINOS

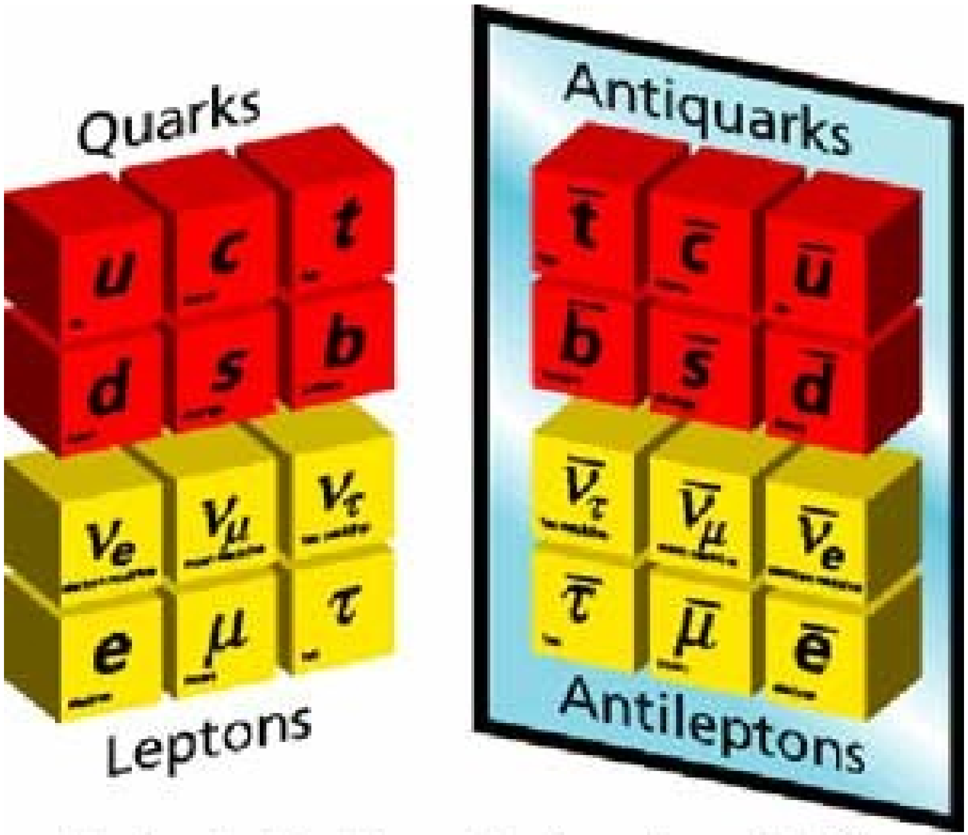
Accelerator neutrino oscillation

Reactor neutrino oscillation

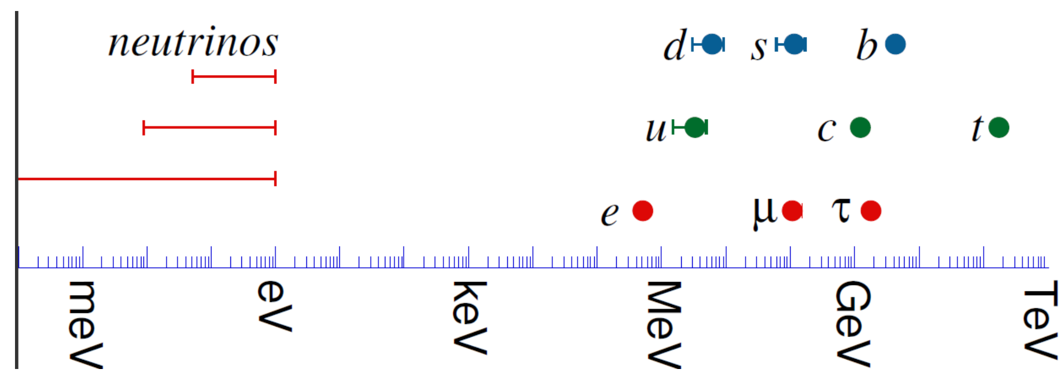


Daya Bay

Why Neutrino?



The Standard Model contains 3 neutrinos of definite flavor, and a set of corresponding anti-particles.



Beyond Standard Model

Neutrinos are essential building blocks in our universe

Two-Flavor Neutrino Mixing

Neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) produced in weak interaction are different from mass eigenstates (ν_1, ν_2, ν_3).

$$\begin{pmatrix}\nu_\alpha \\ \nu_\beta\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$

α, β: flavor states
1, 2: mass states

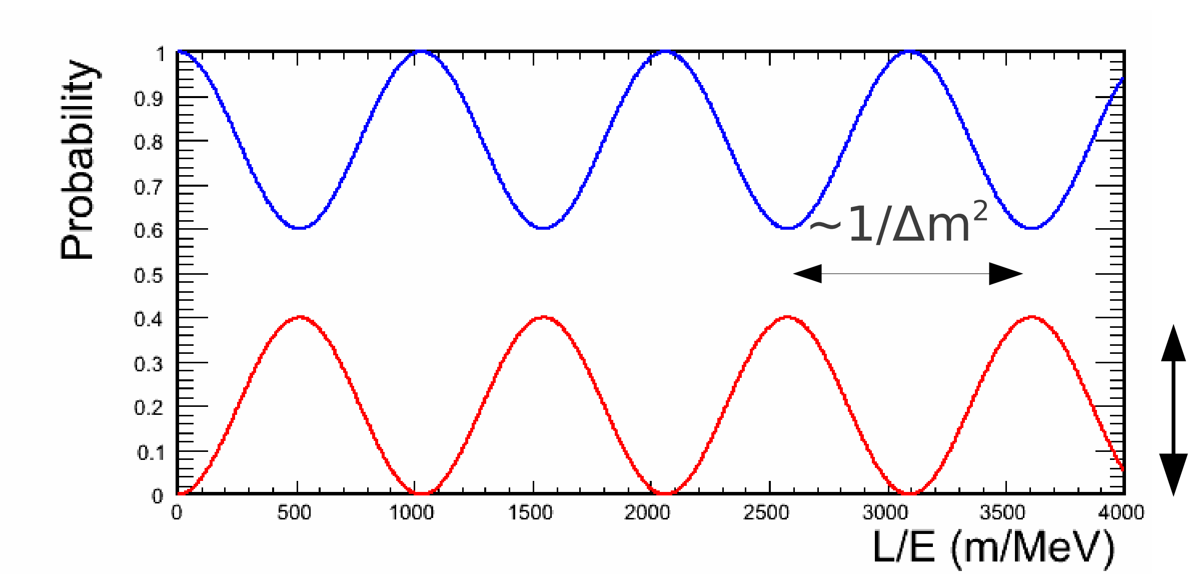
Appearance Mode:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\,\Delta m^2[eV^2]\frac{L[m]}{E[MeV]}\right)$$

$$\Delta m^2 \equiv m_2^2 - m_1^2$$

Disappearance Mode:

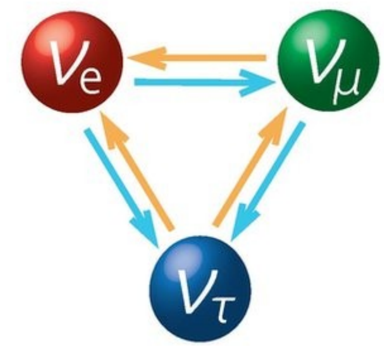
$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - P(\nu_\alpha \rightarrow \nu_\beta)$$



sin²(2θ)

We want to measure θ and Δm²

Three-Flavor Neutrino Mixing



$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle$$

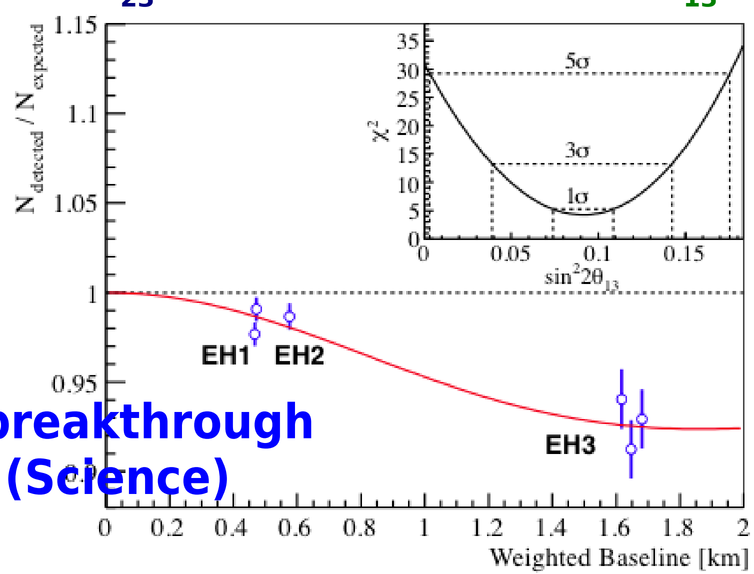
PMNS Mixing Matrix

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

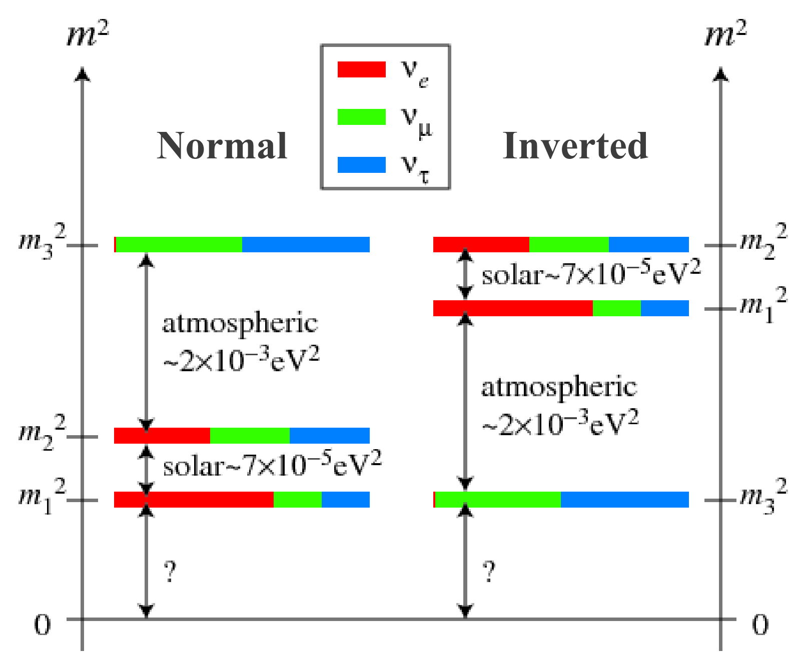
$c_{ij} \equiv \cos\theta_{ij}$

$s_{ij} \equiv \sin\theta_{ij}$

atmospheric	**reactor**	**solar**
$\theta_{23} \sim 45°$	$\theta_{13} \sim 9°$	$\theta_{12} \sim 34°$



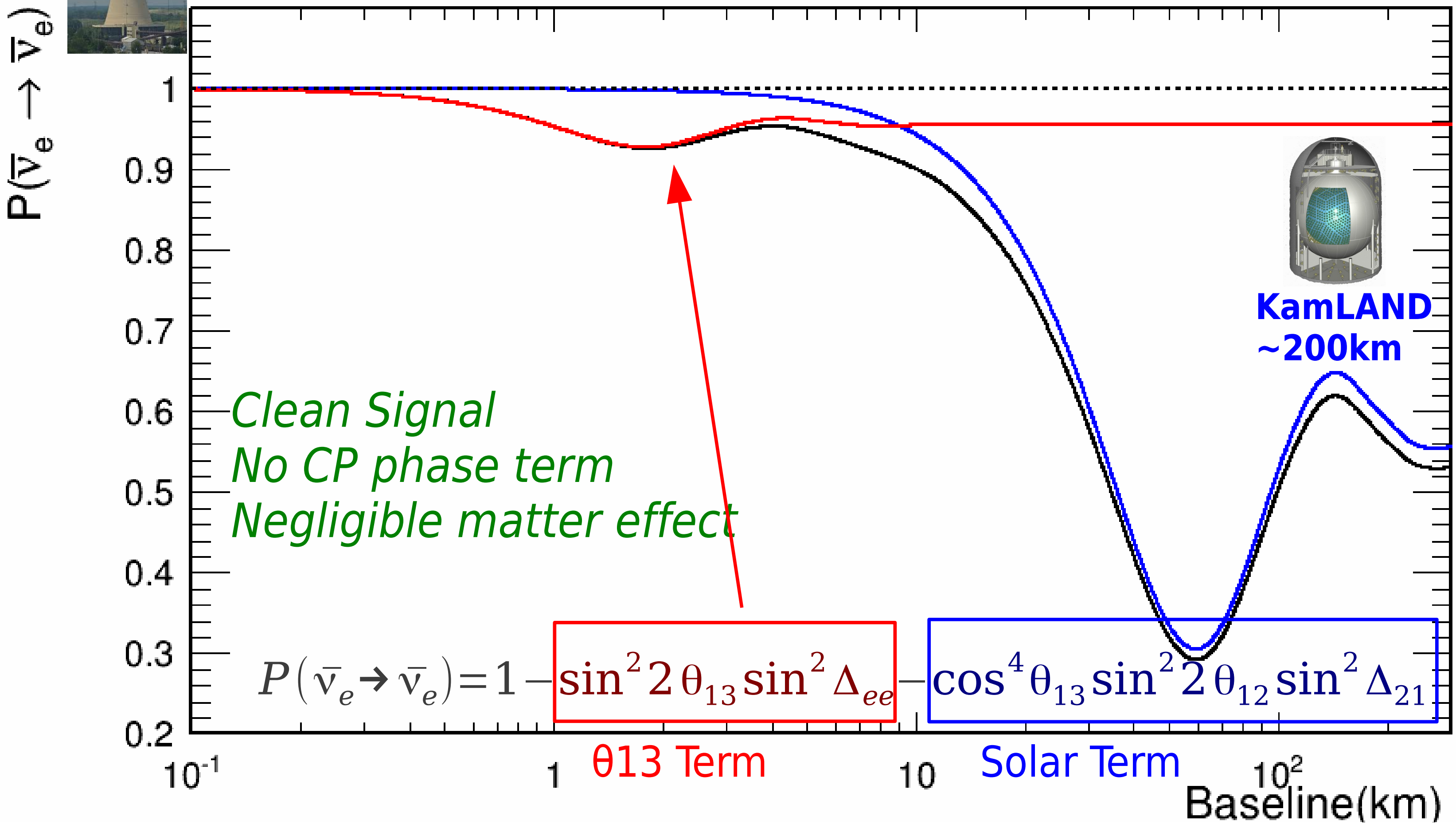
Top 10 breakthrough of 2012 (Science)



The gateway for measuring neutrino mass hierarchy and CP violation is open

Reactor Neutrinos Oscillation

θ_{13} can be revealed by a deficit of reactor antineutrinos at ~2km

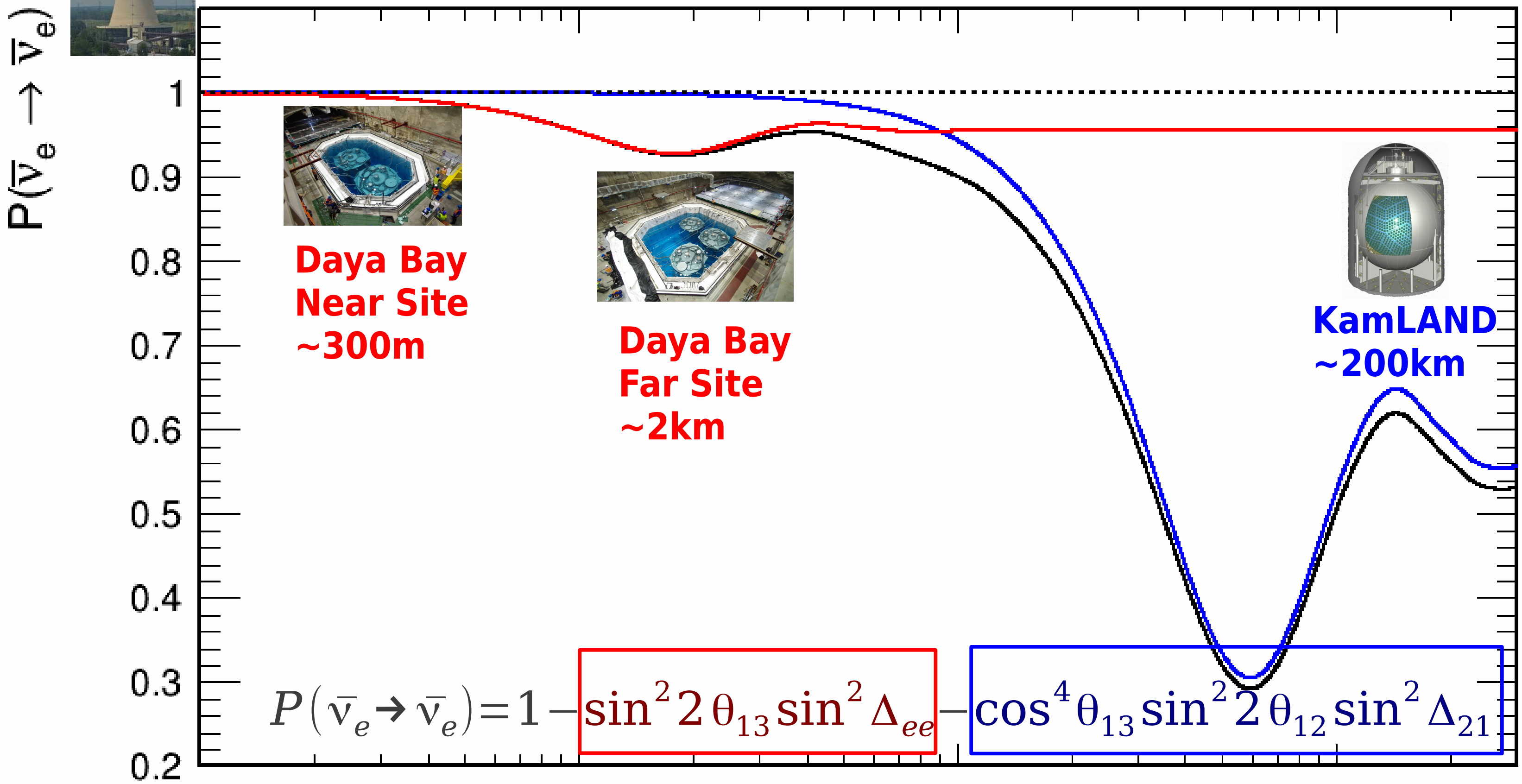


Define
$$\sin^2\Delta_{ee} = \cos^2\theta_{12}\sin^2\Delta_{31}+\sin^2\theta_{12}\sin^2\Delta_{32}$$
$$\approx 0.7\cdot\sin^2\Delta_{31}+0.3\cdot\sin^2\Delta_{32}$$

$$\Delta_{ij}\simeq 1.27\,\Delta m_{ij}^2(eV^2)\frac{L(m)}{E(MeV)}$$

Relative Measurement

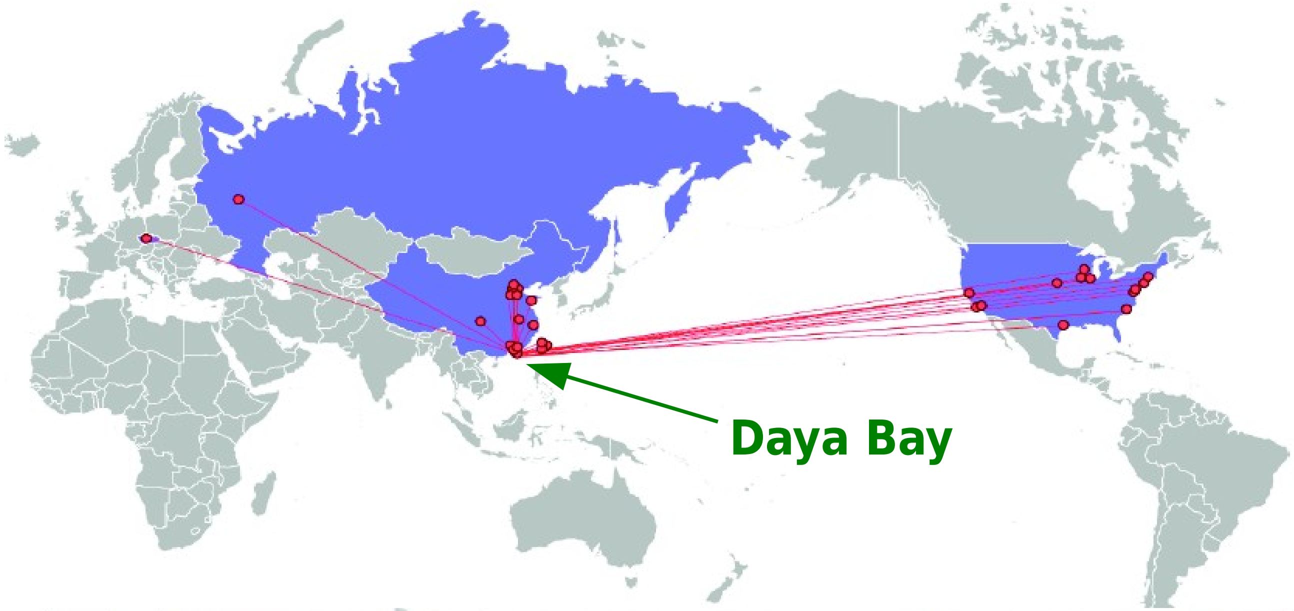
- Cancel absolute reactor flux uncertainty
- Cancel absolute detector efficiency uncertainty



$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right]$$

Far/Near Neutrino Ratio	Detector Target Mass	Distance from Reactor	Detector Efficiency	Survival Probability ($\theta 13$)

Daya Bay Collaboration



Asia (21)

Beijing Normal Univ., Chendu Univ. of Sci. and Tech., CGNPG, CIAE, Chinese Univ. of Hong Kong, Dongguan Univ. of Tech., IHEP, Nanjing Univ., Nankai Univ., National Chiao Tung Univ., National Taiwan Univ., National Untied Univ., NCEPU, Shangdong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., Univ. of Hong Kong, USTC, Xi'an Jiao Tong Univ., Zhongshan Univ.

North America (17)

BNL, Caltech, LBNL, Illinois Inst. Tech., Iowa State Univ., Printon, RPI, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Illinois-Urbana-Champaign, Univ. of Wisconsin, Virginia Tech., William & Mary, Siena College, Yale

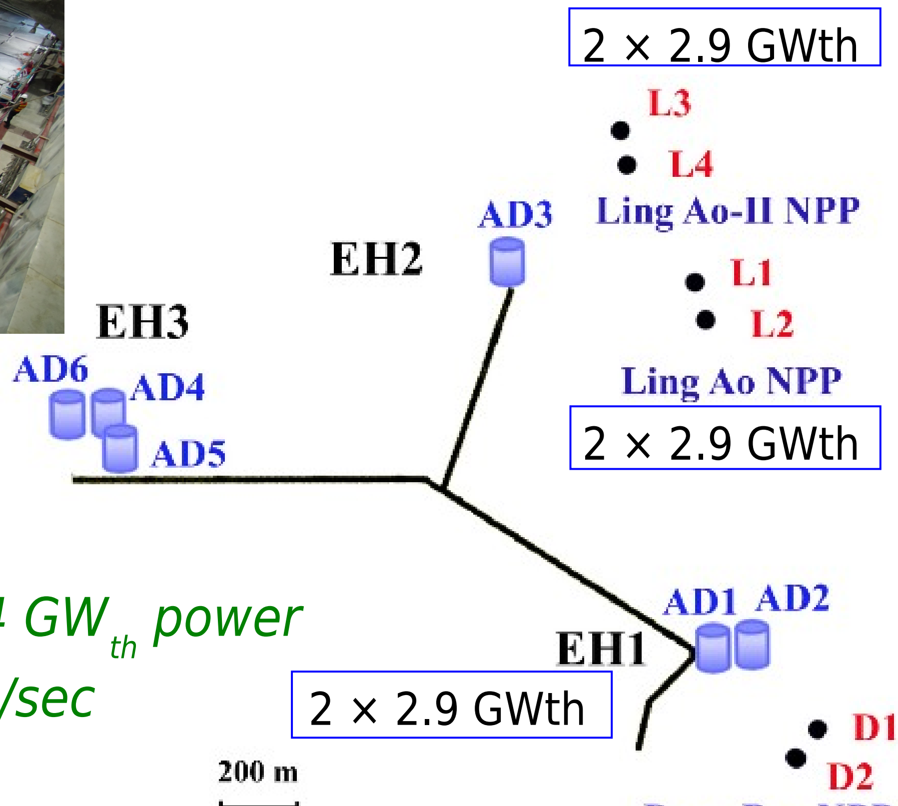
Europe (2)

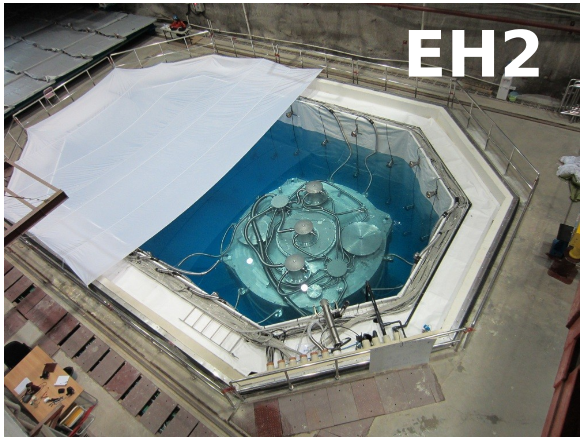
Charles University, Czech Republic;
JINR, Dubna, Russia

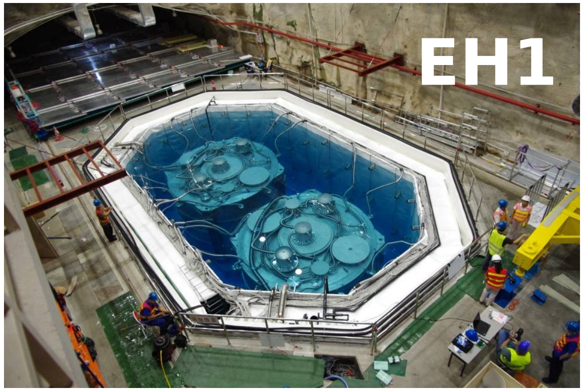
40 institutions
~230 collaborators

Daya Bay Experimental Layout

6 Antineutrino Detectors (ADs) in 3 underground experimental halls (EHs).







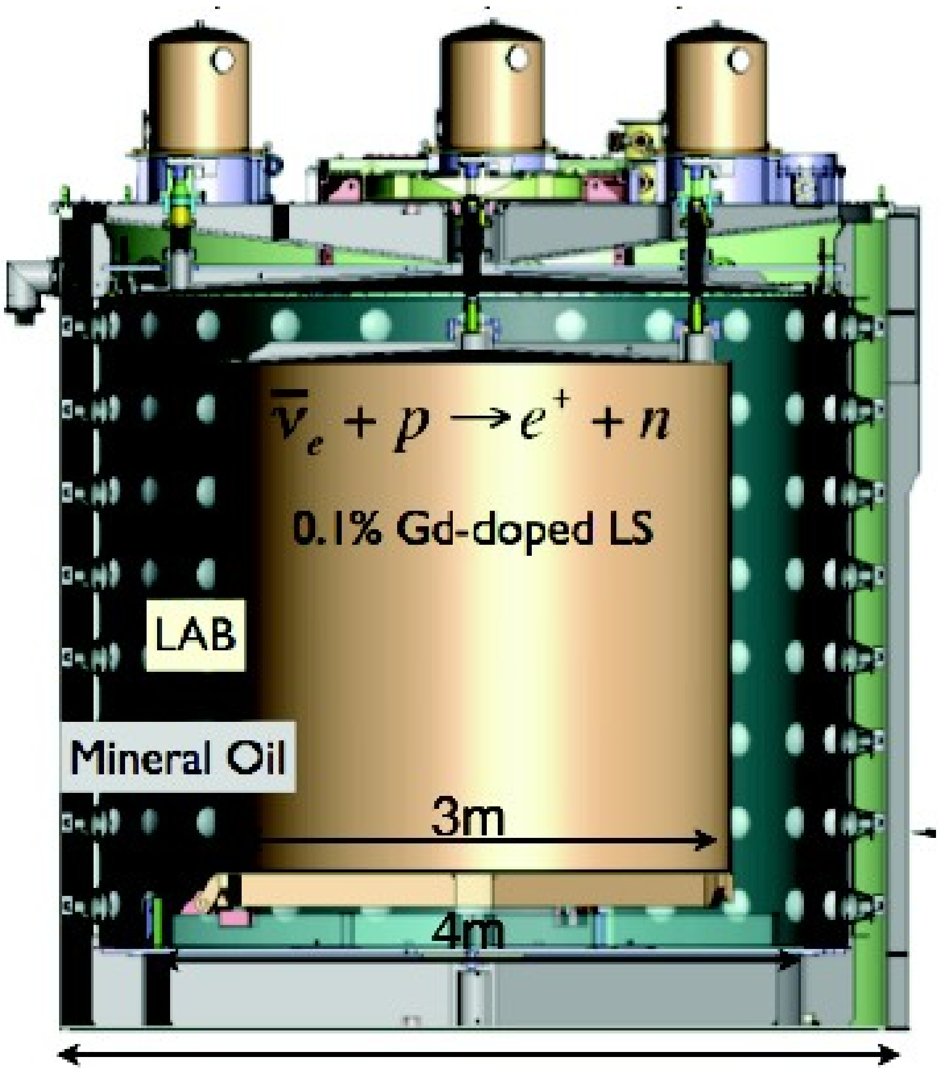
6 cores produce 17.4 GW_{th} power

~35 x 10^{20} neutrinos/sec

	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

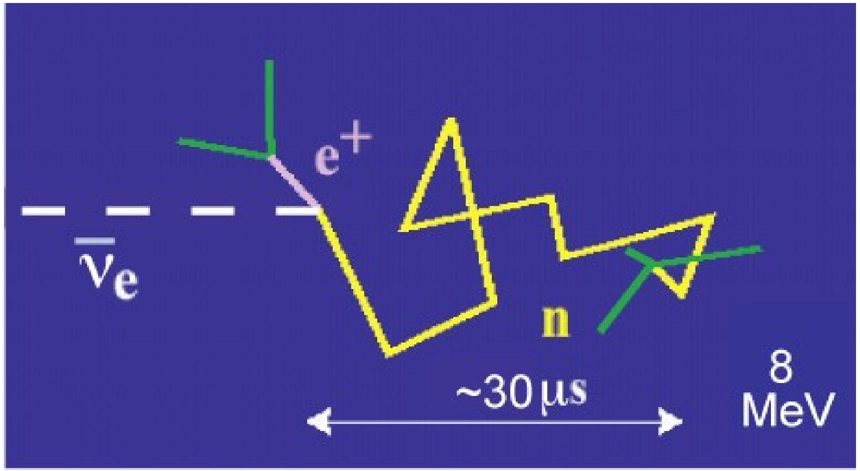
TABLE I. Overburden (m.w.e), muon rate R_μ (Hz/m^2), and average muon energy E_μ (GeV) of the three EHs, and the distances (m) to the reactor pairs.

Daya Bay Antineutrino Detectors (AD)



6 functionally identical 3-zone detectors

Very well defined target region



$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\downarrow$$
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$

Inverse beta decay (IBD)

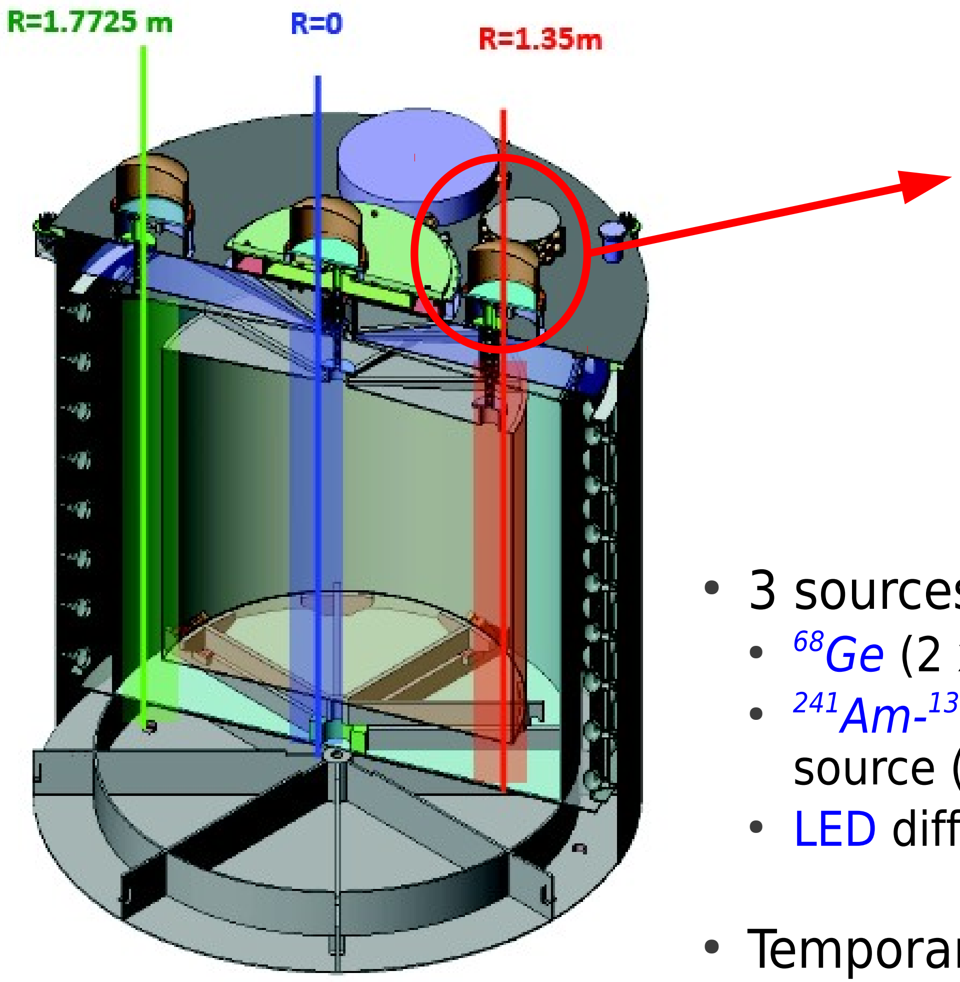
Prompt Positron:

- Carries antineutrino energy
- $E_{Prompt} \simeq E_{\nu} - 0.8\, MeV$

Delayed Neutron Capture

- $\langle \sum E_{\gamma} \rangle = 8.05\, MeV$
- Efficiently tag antineutrino signal

Automatic Calibration Units (ACU)



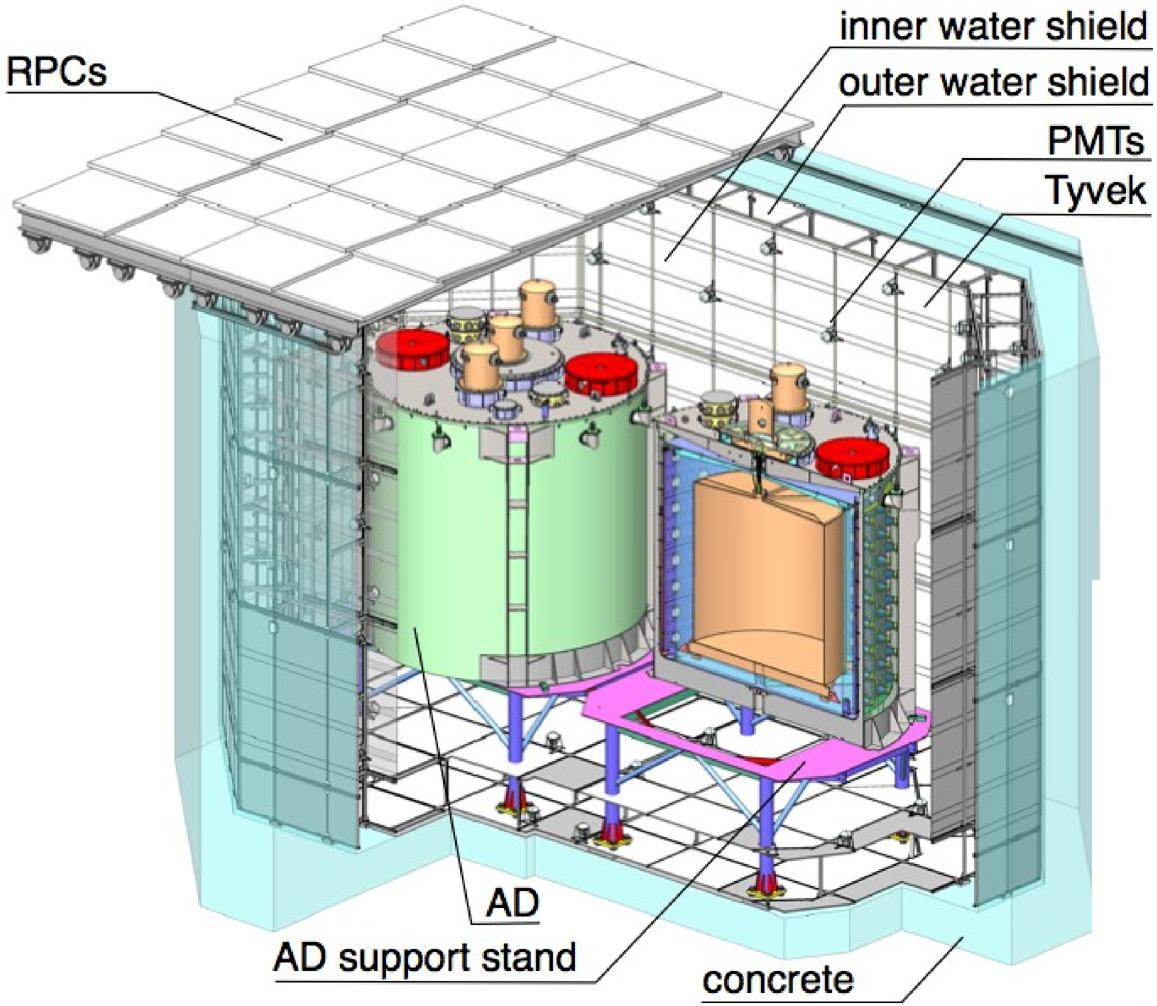
- 3 sources for each 3 z axis on a turntable
  - ^{68}*Ge* (2 x 0.511 MeV γ's)
  - ^{241}*Am*-^{13}*C* neutron source (3.5 MeV n) + ^{60}*Co* gamma source (1.173+1.332 MeV γ's)
  - LED diffuser ball for timing and gain

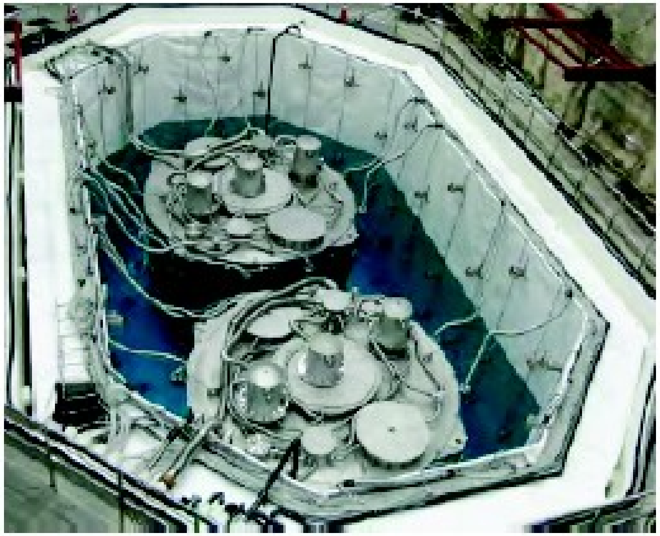
- Temporary special calibration sources:
  - γ: ^{137}*Cs* (0.662MeV), ^{54}*Mn*(0.835MeV), ^{40}*K* (1.461MeV)
  - n: ^{241}*Am*^{9}*Be*, ^{239}*Pu*^{13}*C*

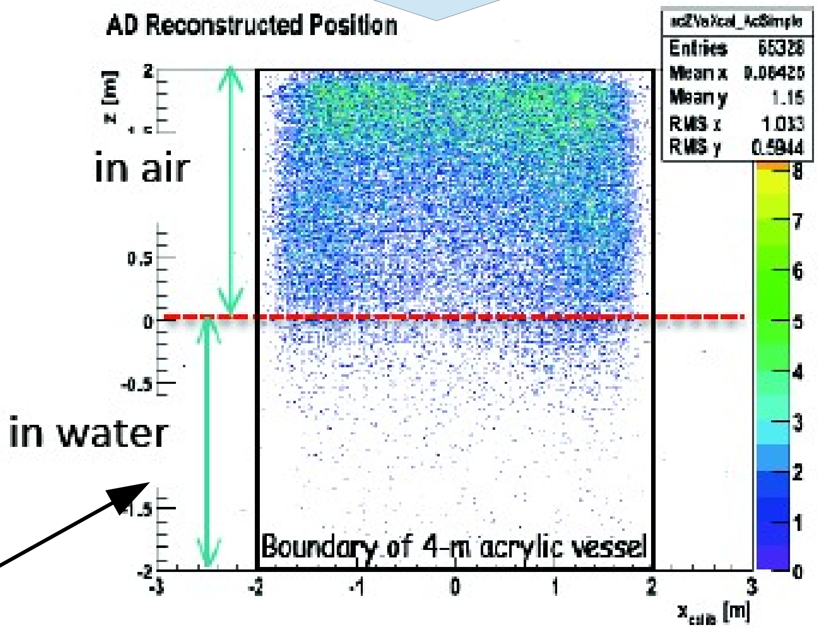
3 Automatic calibration "robots" on each detector

Muon Tagging System

Dual Tagging system: 2.5 meter thick two-section water shield and RPCs.







Reduce radioactive backgrounds

AD reconstructed position
during water pool filling

Analysis Data Sets

A. Two-detector data taking:

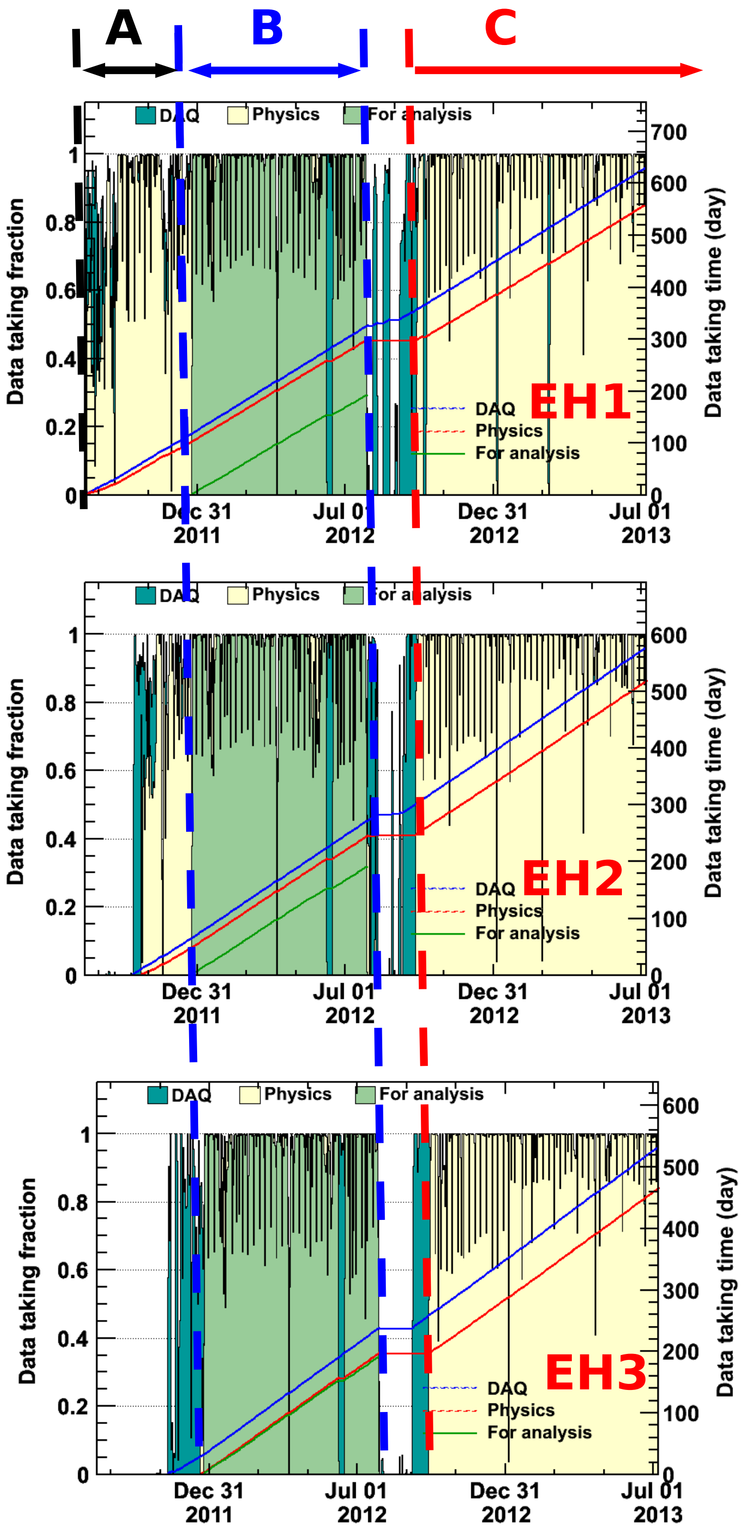
- Sep 23, 2011 – Dec. 23, 2011 [90 days]
- Side-by-side comparison of 2 detectors
- *NIM A **685**, 78-97 (2012)*

B. Six-detector data taking:
[This analysis]

- Dec. 24, 2011 – Jul. 28, 2012 [217 days]
- Full 6AD data set, 55% more statistics than CPC result
- Previous θ_{13} measurements:
  - *PRL. **108**, 171803 (2012)* [55 days]
  - *CPC **37**, 011001 (2013)* [139 days]

C. Eight-detector data taking:

- Start from Oct.28, 2012



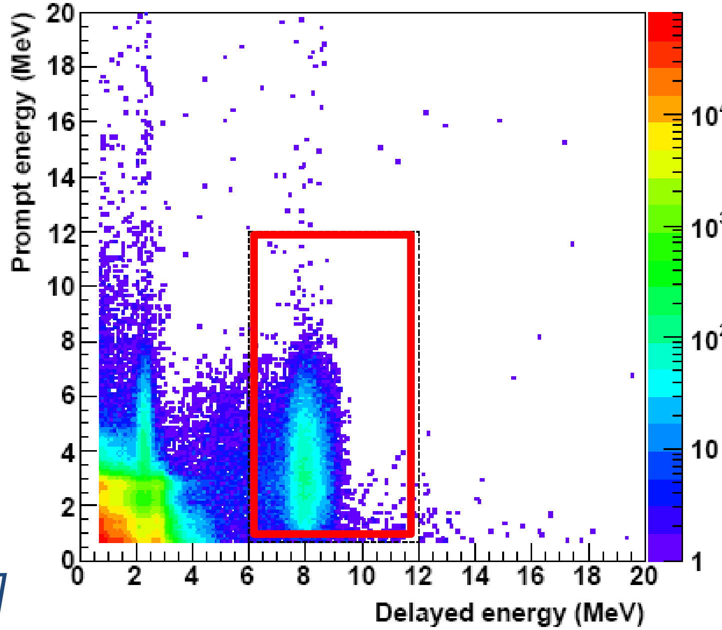
Antineutrino (IBD) Selection

Use IBD Prompt + Delayed correlated signal to select antineutrinos

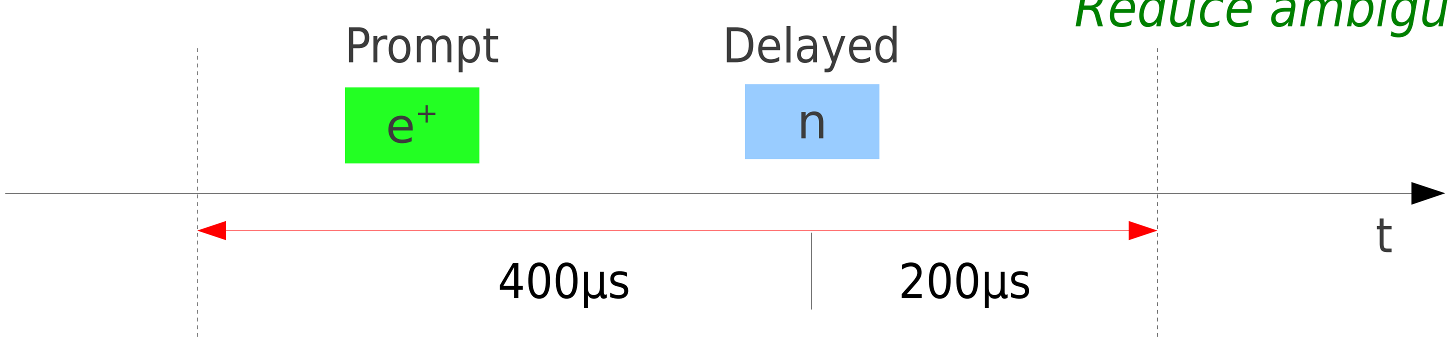
Selection:

- Reject PMT Flashers
- Prompt Positron: *0.7 MeV < Ep < 12 MeV*
- Delayed Neutron: *6.0 MeV < Ed < 12 MeV*
- Capture time: *1 μs < Δt < 200 μs*
- Muon Veto for delay neutron:
  - Water Pool Muon (nHit>12): *Reject [-2μs, 600μs]*
  - AD Muon (>3000PE): *Reject [-2μs, 1400μs]*
  - AD Shower Muon (>3 x 10^5 PE): *Reject [-2μs, 0.4s]*
- Multiplicity:

  No additional prompt-like signal in 400μs before the delayed signal, and no delayed-like signal in 200μs after the delayed signal



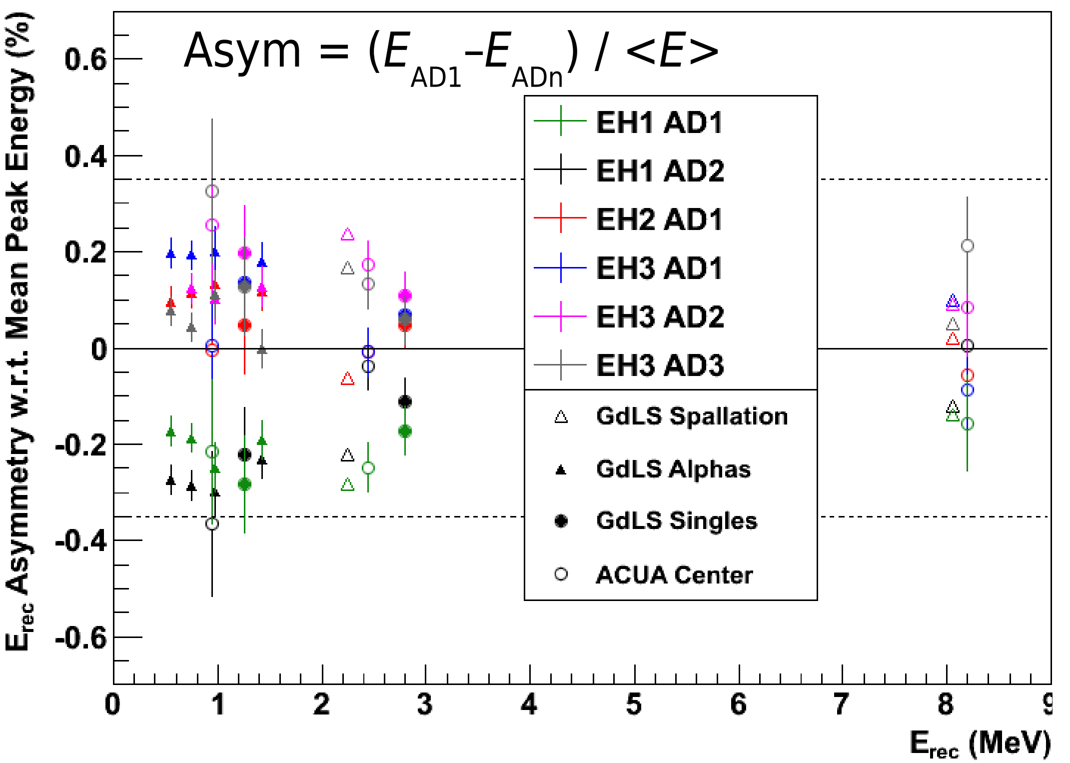
Reduce ambiguity pairs



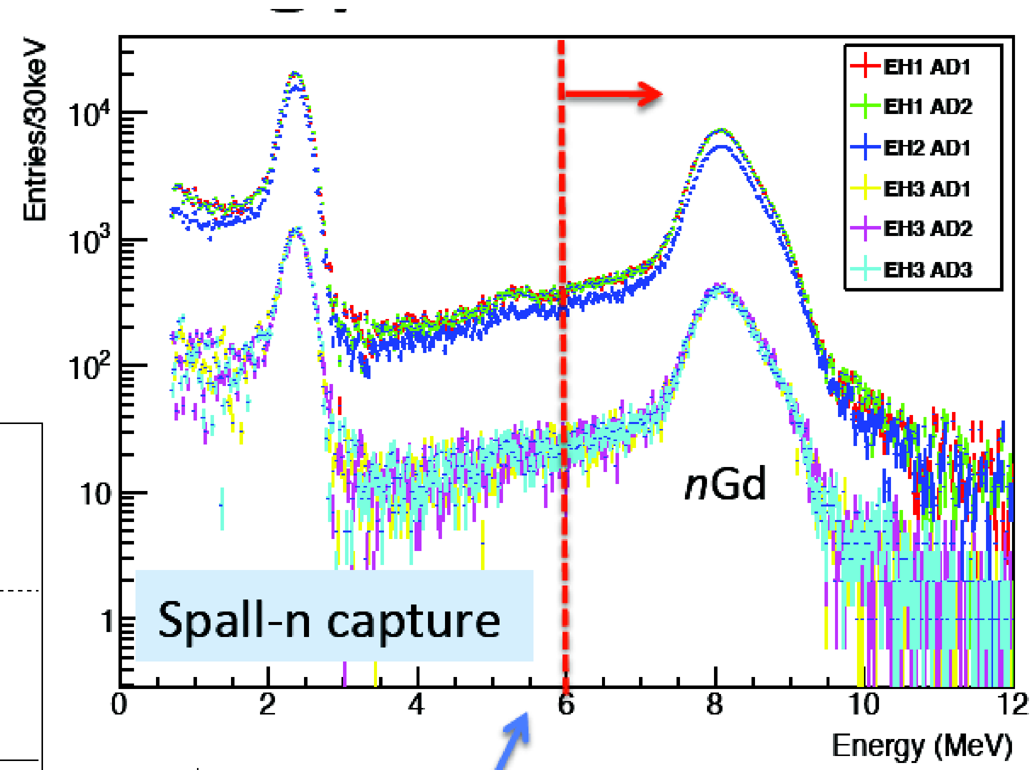
Delayed Energy Cut

Some *n*Gd gammas escape scintillator region, visible as tail of *n*Gd energy peak

Use variations in energy peaks to constrain relative efficiency



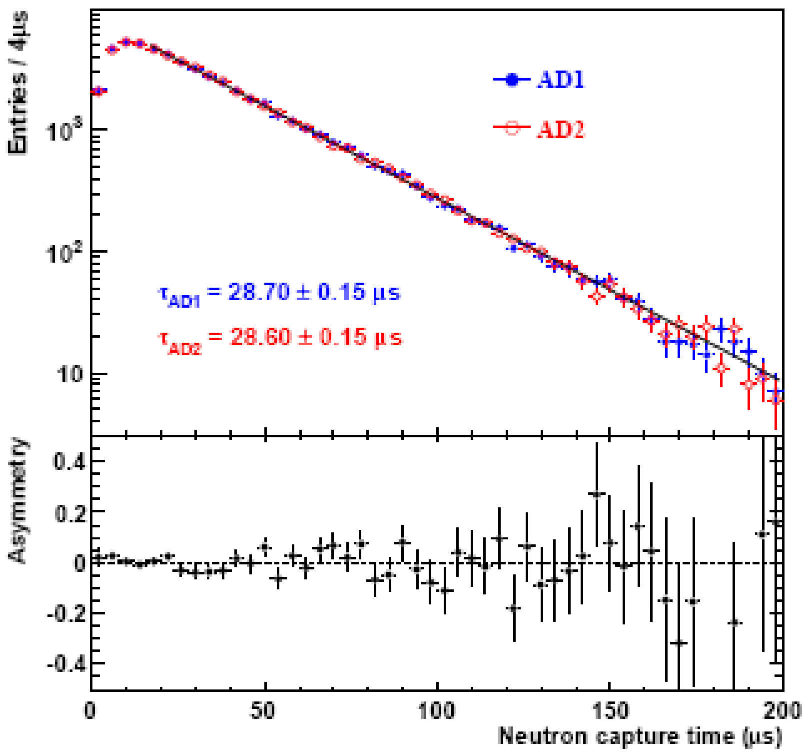
energy peak variation: <0.35%

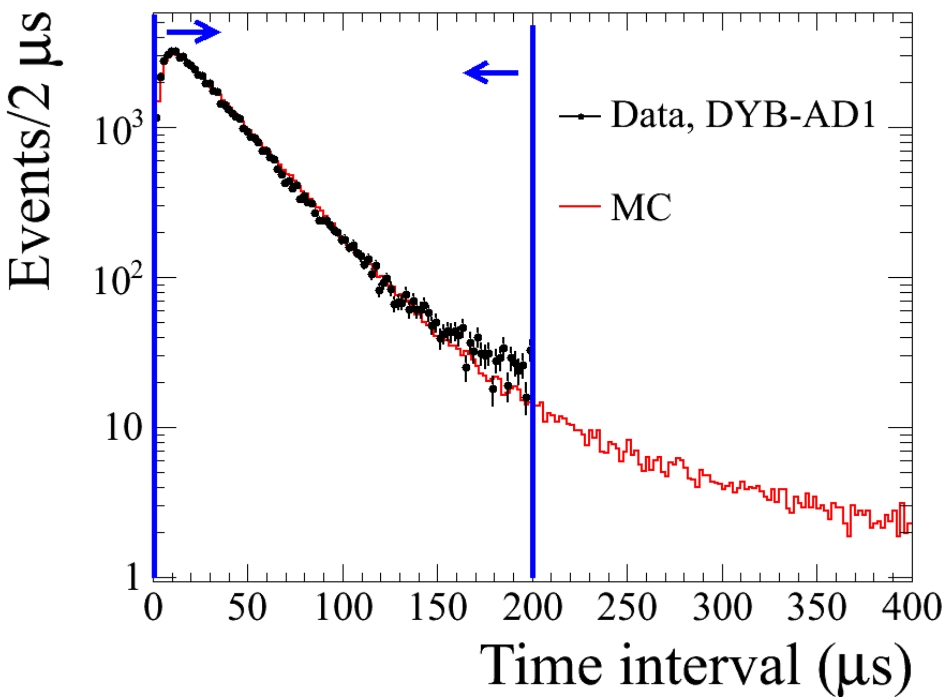


0.35% relative energy uncertainty between detectors can cause ~0.12% efficiency variation

Capture Time and Gd Capture Ratio

Consistent neutron capture times in all detectors.
Capture time in each detector also constrains Gd capture ratio.





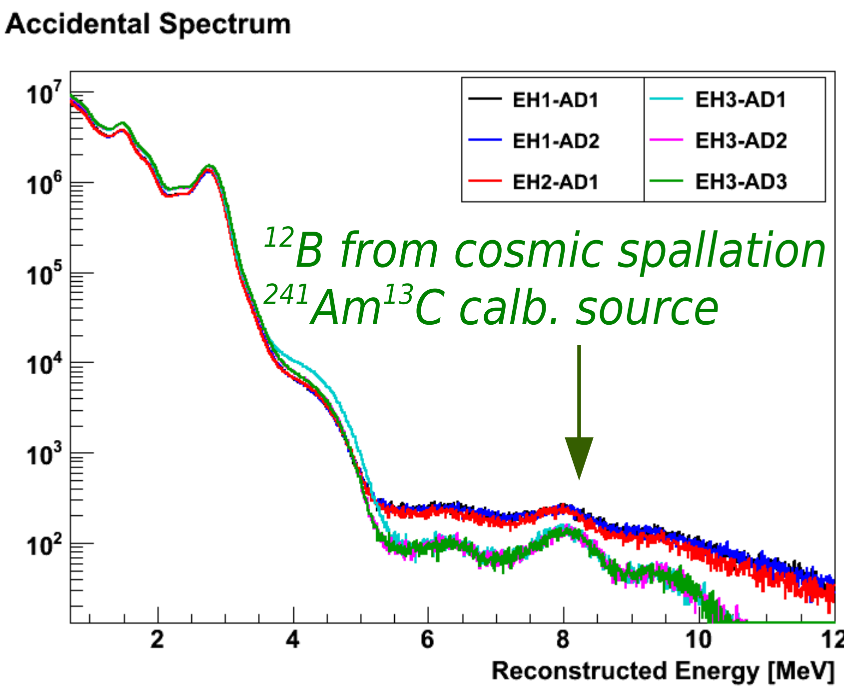
Measurement of neutron capture time from Am-C source constrains uncertainty in relative H/Gd capture efficiency to <0.1% among detectors.

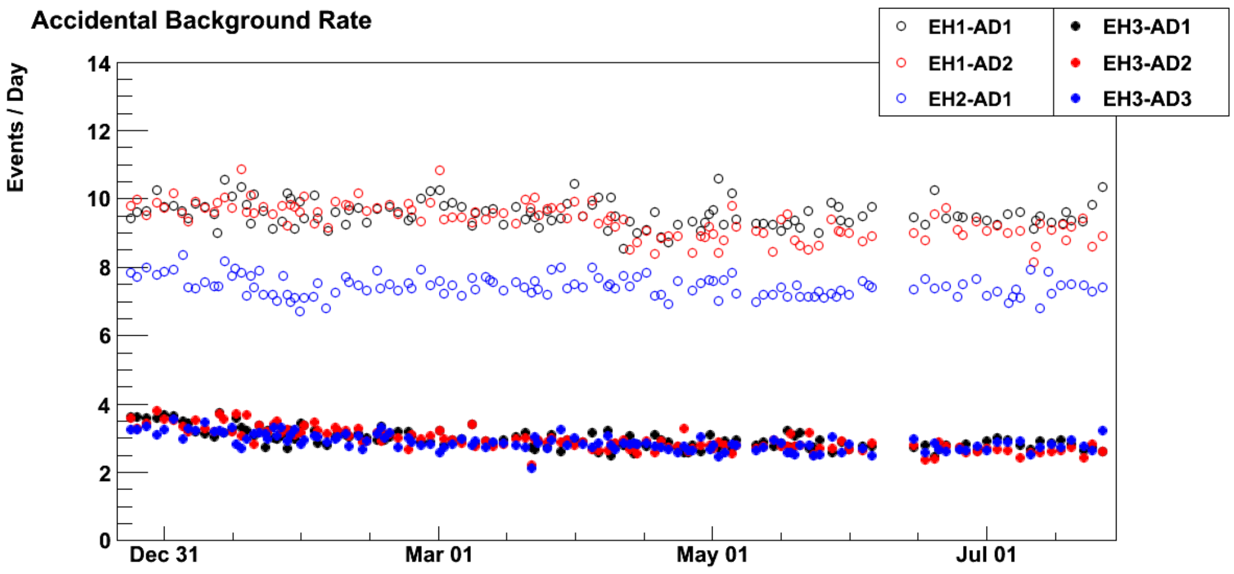
Relative detector efficiency estimated within 0.01% by considering possible variations in Gd concentration.

*Data has background included, MC is pure IBD signal.

Accidental Background

Two single signals can accidentally mimic an antineutrino (IBD) signal

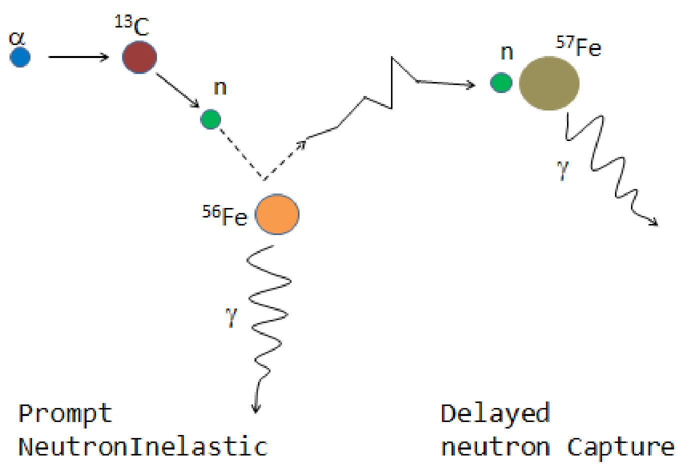


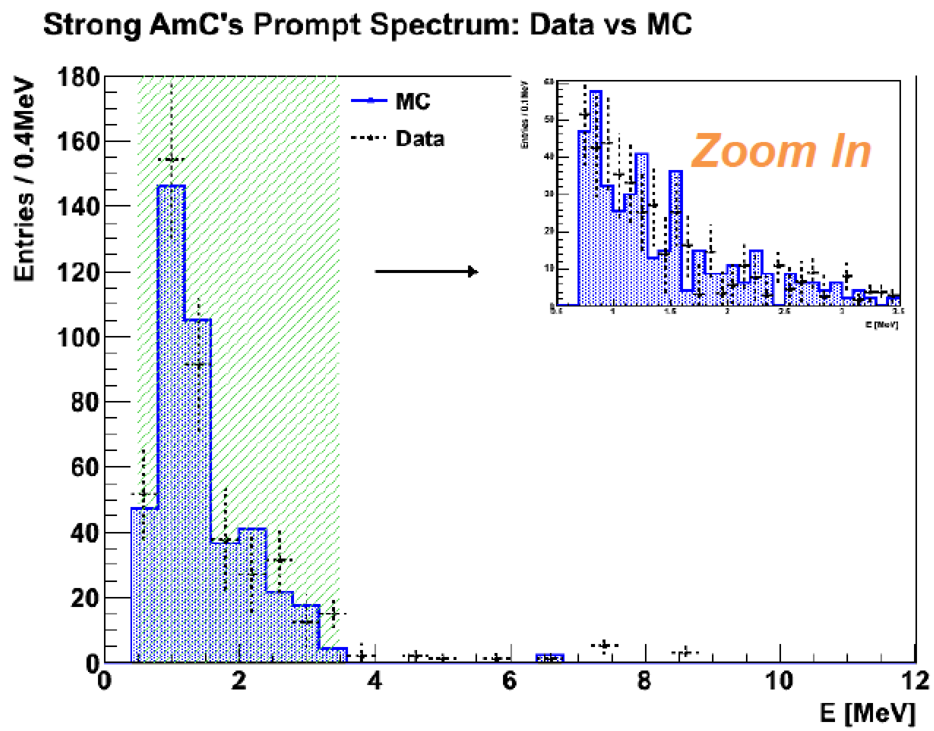


- Accidental background can be accurately modeled using uncorrelated signal in data
- The decreasing rate of accidentals could be related with the Radon decay inside of the water pool
- B/S to 4% (1.5%) of far (near) signal

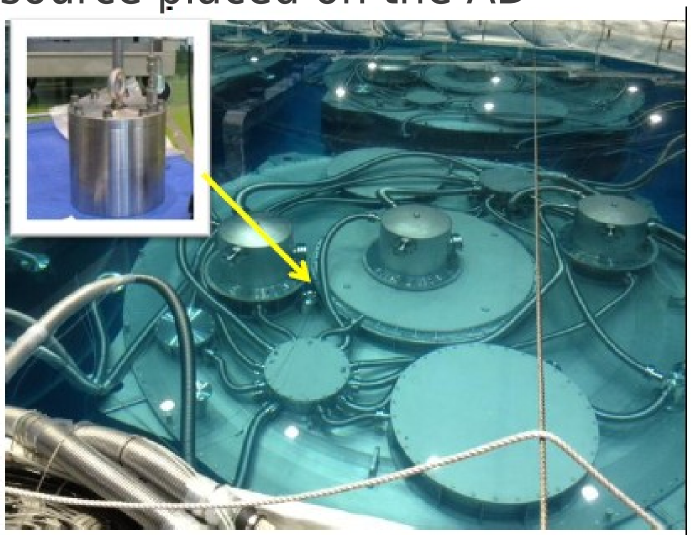
Background: ^{241}Am-^{13}C Neutrons

0.75 Hz neutron source in ACU can mimic IBD via inelastic scattering and capture on iron.





A special x80 stronger AmC source placed on the AD



Background from our calibration source

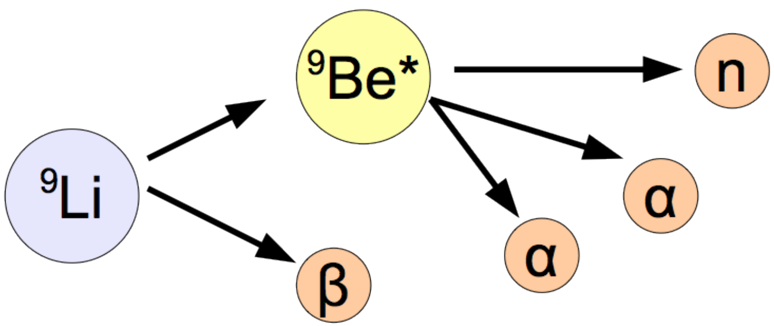
Background rate and spectrum constrained using intensive source

Constrain far site B/S to 0.36±0.16%

Cosmogenic background: ^{9}Li and ^{8}He

β-n decay:

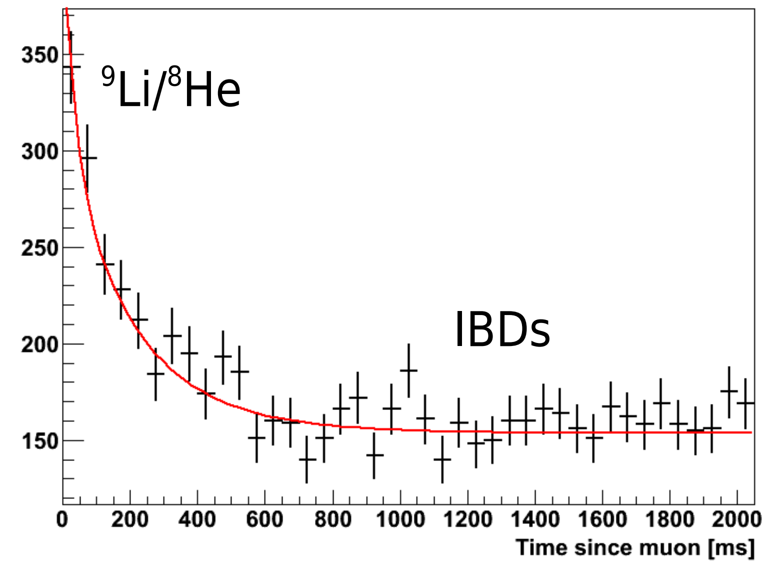
- Prompt: β-decay
- Delayed: neutron capture



Generated by cosmic rays

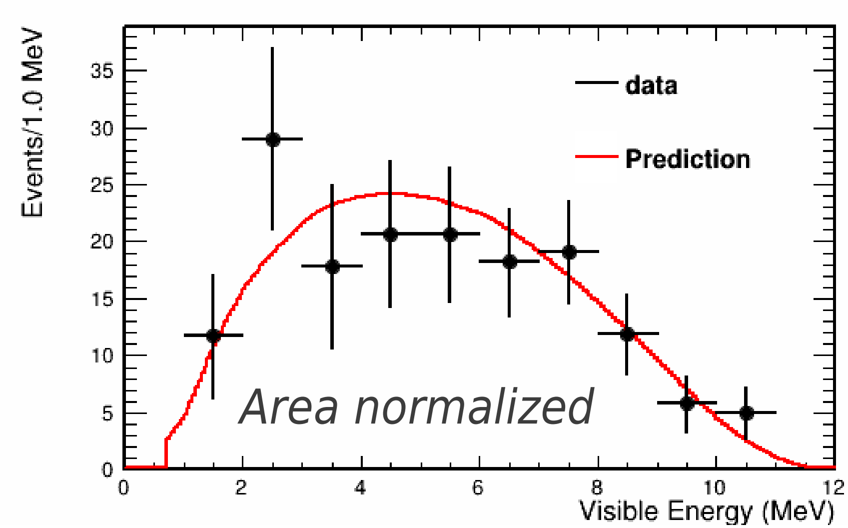
long-lived $\tau^{1/2}$ (^{9}Li/^{8}He) = 178 ms / 119 ms

^{9}Li/^{8}He are measured by fitting the distribution of IBD candidates vs. time since muon



The spectra of ^{9}Li/^{8}He is predicted from a simulation benchmarked with external data and which accounts for all daughter particles.

muon veto cuts control B/S to ~0.3% (0.4%) of far (near) signal



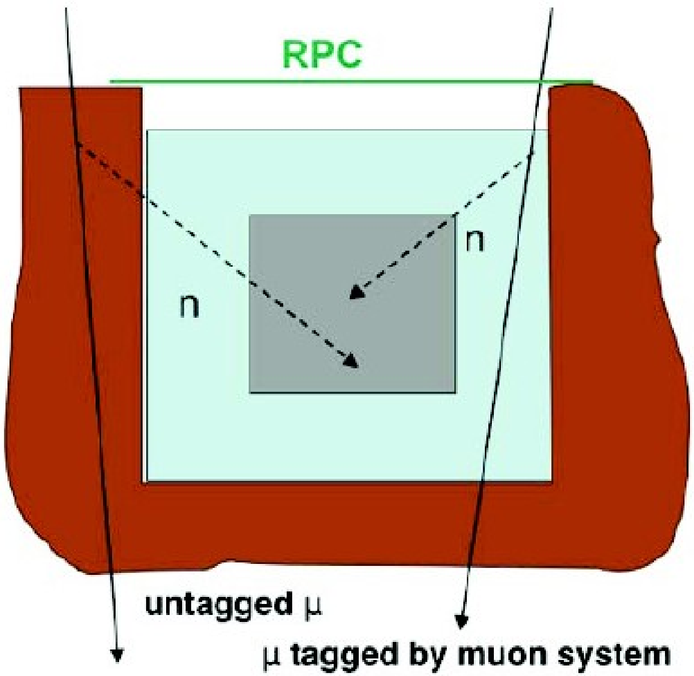
Cosmogenic background: Fast Neutrons

Fast Neutrons:

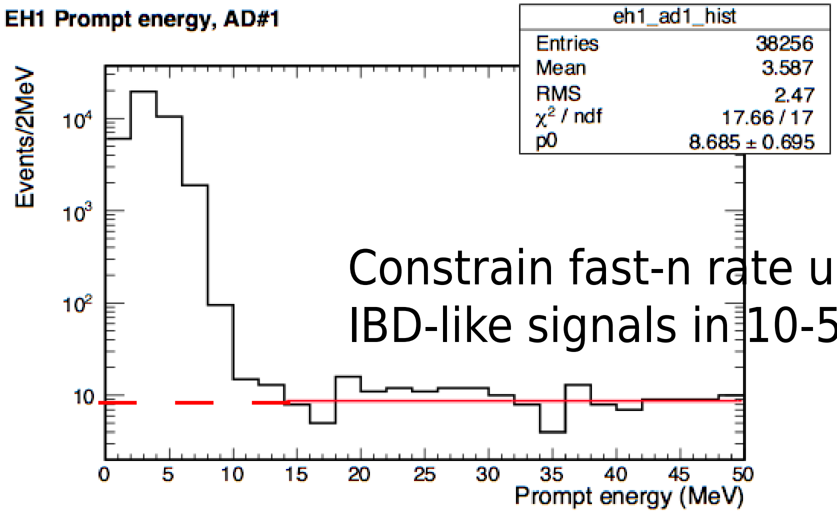
Energetic neutrons produced by cosmic rays

Mimics antineutrino (IBD) signal:

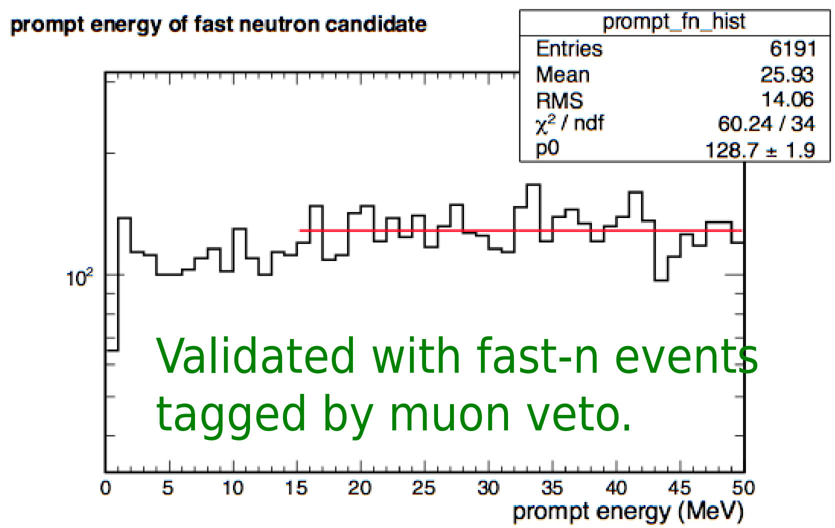
- Prompt: Neutron collides in target
- Delayed: Neutron captures on Gd



Muon veto cuts control B/S to 0.06% (0.1%) of far (near) signal



Constrain fast-n rate using IBD-like signals in 10-50 Me



Validated with fast-n events tagged by muon veto.

Data Set Summary

	EH1		EH2	EH3		
	AD1	AD2	AD3	AD4	AD5	AD6
Antineutrino candidates	101290	102519	92912	13964	13894	13731
DAQ live time (day)	191.001		189.645	189.779		
Efficiency	0.7957	0.7927	0.8282	0.9577	0.9568	0.9566
Accidentals (/day/AD)*	9.54±0.03	9.36±0.03	7.44±0.02	2.96±0.01	2.92±0.01	2.87±0.01
Fast neutron (/day/AD)*	0.92±0.46		0.62±0.31	0.04±0.02		
^{8}He/^{9}Li (/day/AD)*	2.40±0.86		1.20±0.63	0.22±0.06		
Am-C corr. (/day/AD)*	0.26±0.12					
^{13}C(α, n)^{16}O (/day/AD)*	0.08±0.04	0.07±0.04	0.05±0.03	0.04±0.02	0.04±0.02	0.04±0.02
Antineutrino rate* (/day/AD)	**653.30 ± 2.31**	**664.15 ± 2.33**	**581.97 ± 2.07**	**73.31 ± 0.66**	**73.03 ± 0.66**	**72.20 ± 0.66**

**rate are muon and multiplicity cut efficiency corrected.*

Over 300,000 antineutrino interactions

Total Background/Signal ratio is ~5% at Far site, ~2% at Near site

Neutrino Flux Prediction

$$S(E_\nu)=\frac{W_{th}}{\sum_i f_i e_i}\sum_i^{istopes} f_i S_i(E_\nu)$$

Reactor operator provide:

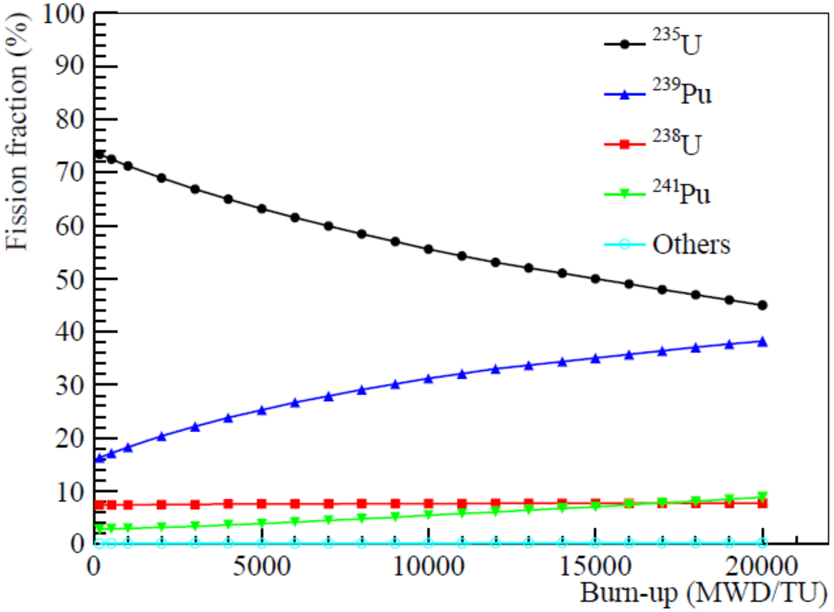
- Thermal power W_{th}
- Relative isotope fission fraction: f_i

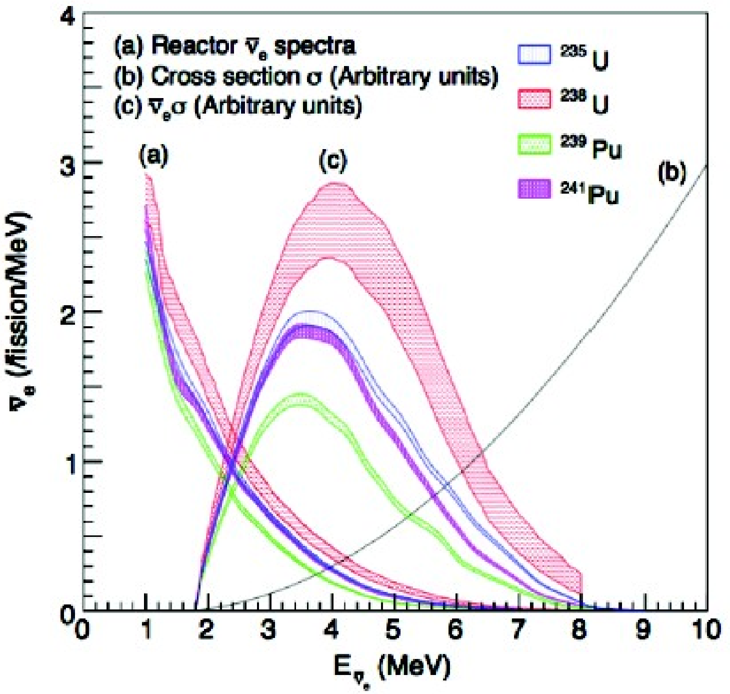
Energy release per fission: e_i

- *V. Kopekin et al., Phys. Atom. Nucl. 67, 1892 (2004)*

Antineutrino spectra per fission: $S_i(E_\nu)$

- *K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)*
- *A. A. Hahn et al., Phys. Lett. B218, 365 (1989)*
- *P. Vogel et al., Phys. Rev. C24, 1543 (1981)*
- *T. Mueller et al., Phys. Rev. C83, 054615 (2011)*
- *P. Huber, Phys. Rev. C84, 024617 (2011)*





Flux model has marginal impact on Far vs. Near oscillation Measurement

Uncertainty Summary

Detector			
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

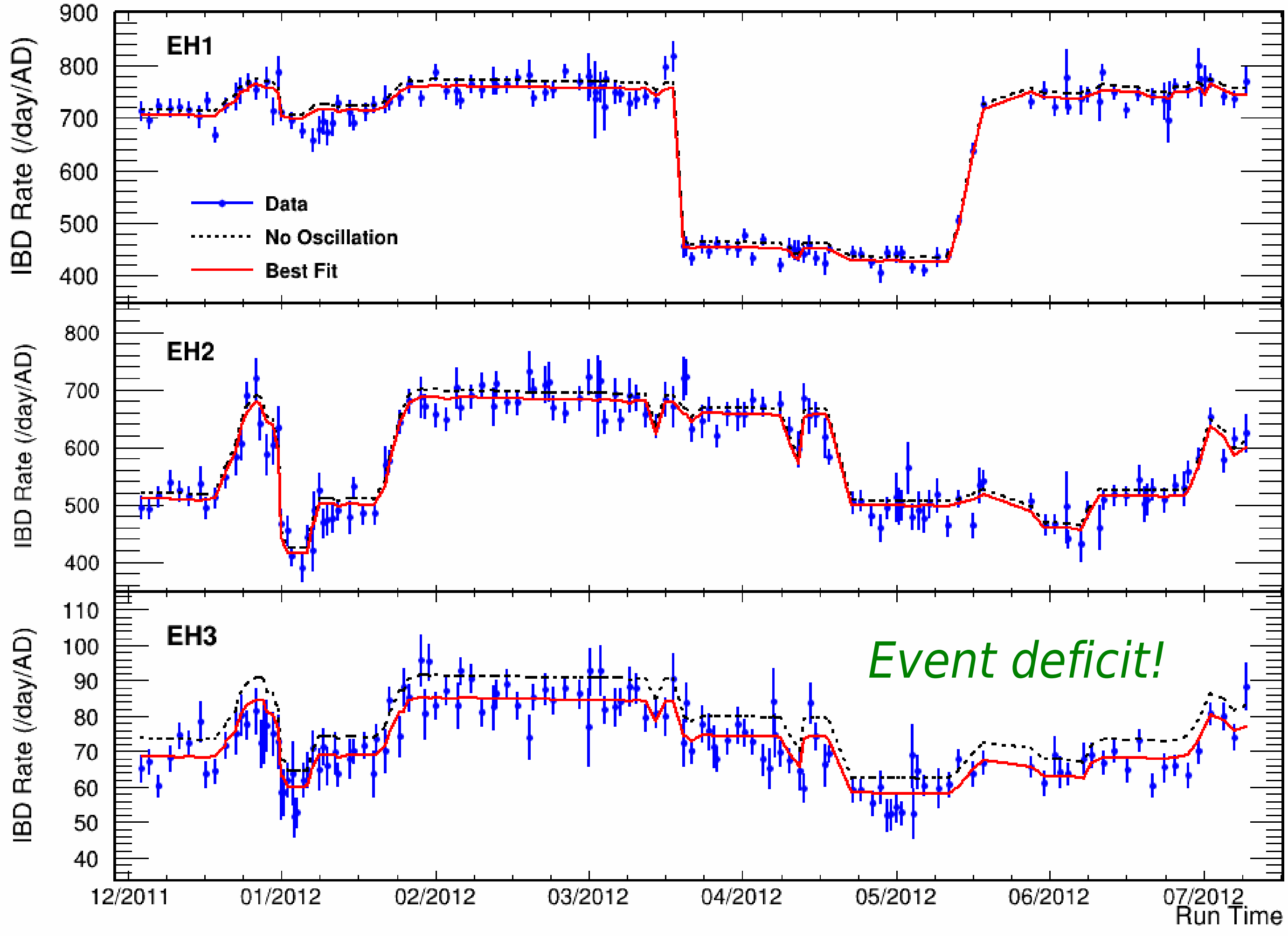
For near/far oscillation, only uncorrelated uncertainties are used

Largest systematics are smaller than far site statistics (~1%)

Influence of uncorrelated reactor systematics further reduced by far vs. near measurement

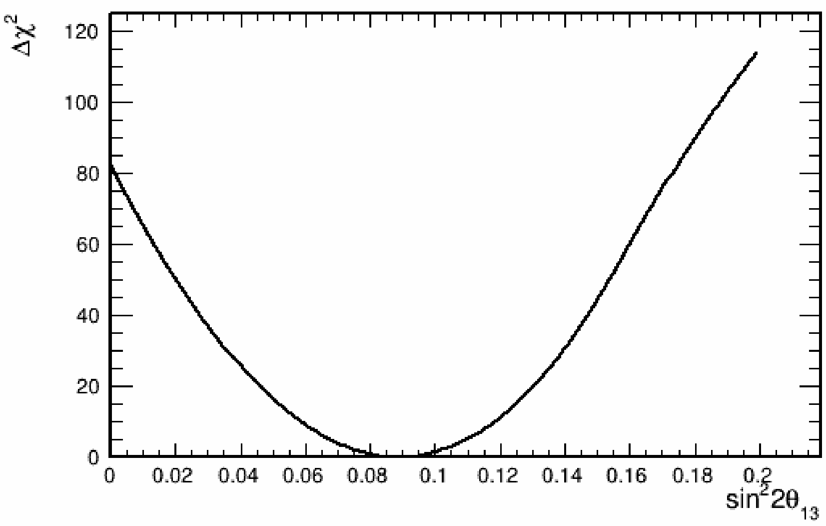
Antineutrino Rate .vs. Time

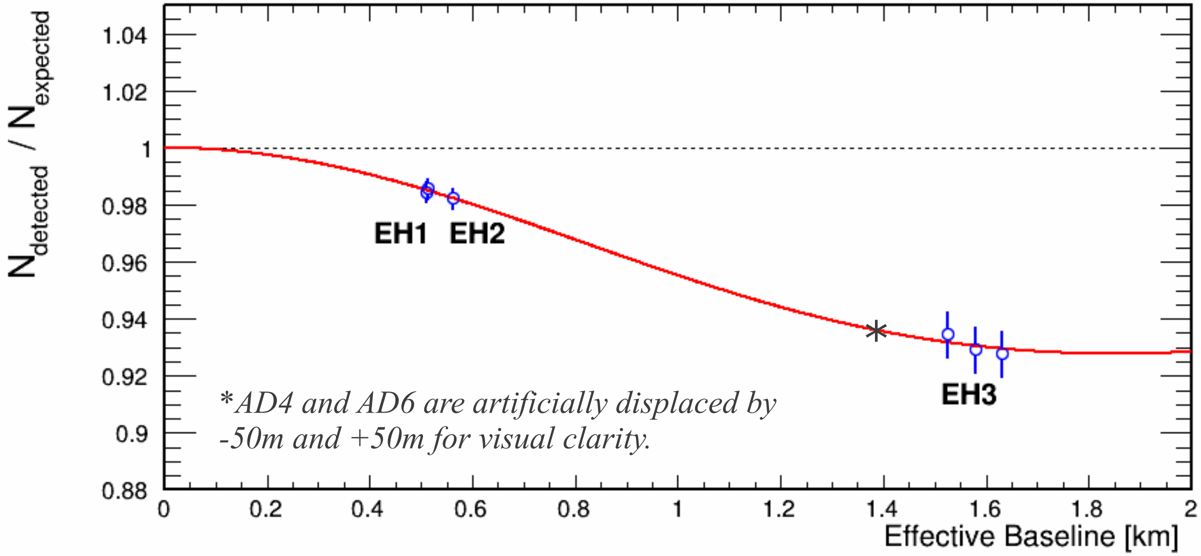
Detected rate fully correlated with reactor flux expectations



- Predicted rate assumes no oscillation
- Normalization is determined by fit to data
- Absolute normalization is within a few percent of expectations

Rate Only Analysis





$$\sin^2 2\theta_{13} = 0.089 \pm 0.009$$

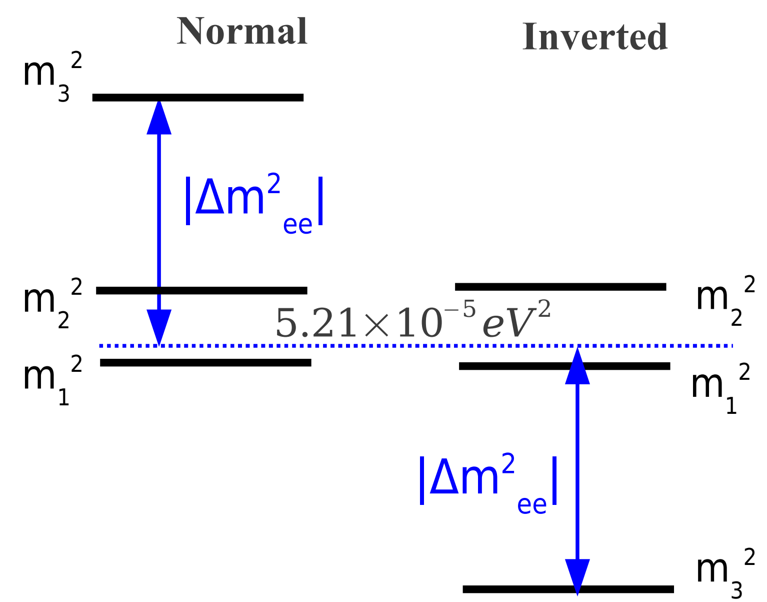
$$\chi^2 / NDF = 0.48/4$$

- **Rate only analysis**
  - Use maximum likelihood method
  - Far vs. near relative measurement [absolute rate is not constrained]
  - Constrain $|\Delta m^2_{ee}|$ to the MINOS $|\Delta m^2_{\mu\mu}| = 2.41^{+0.09}_{-0.10} \times 10^{-3} (eV^2)$ *PRL. 110, 251801 (2013)*
  - Consistent results obtained by different reactor flux models

Why not using the spectrum information?

Spectral Oscillation

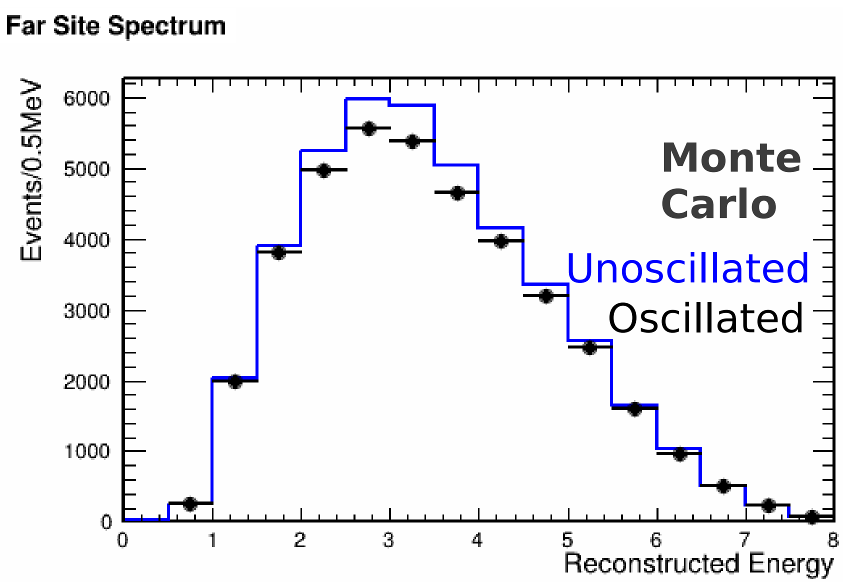
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \boxed{\sin^2 2\theta_{13}} \sin^2\left(1.27 \boxed{\Delta m^2_{ee}} \frac{L}{E}\right)$$

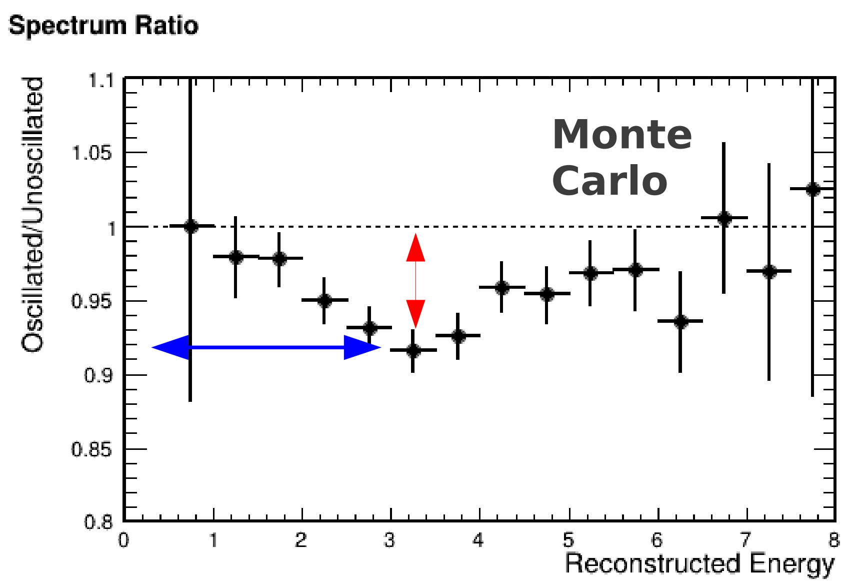


Due to the short baseline, Daya Bay can observe one effective $|\Delta m^2_{ee}|$, which is is a constant shift of $|\Delta m^2_{32}|$ for two mass hierarchies .

$$|\Delta m^2_{ee}| \approx |\Delta m^2_{32}| \pm 5.21\times10^{-5} eV^2$$

+(-) for Normal (Inverted) Mass Hierarchy





Require detailed understanding of detector energy response

Detector Energy Response

Particle Energy **E_{true}**

Energy Deposition in Scintillator **E_{dep}**

Energy Converted to "Visible" Light **E_{vis}**

Reconstructed Energy **E_{rec}**

Energy Response Non-Linearity

Scintillator Energy Response

- **Scintillator quenching effect**
  - Large ionization energy (dE/dX) emit less light than expected. (Birk's Law)
- **Cerenkov radiation**
  - Particle energy threshold (v>c/n)
  - Particle travel length

Coupled

Readout Electronics Response

- **Charge collection efficiency**
  - Electronics not fully capture late secondary hits
- **PMT signal shaping**
  - Multiple PMT pulses shaping
- **Others**

Energy Model connects reconstructed energy **E_{rec}** and true kinetic energy **E_{true}**

- Applied on the predicted E_{true} spectrum to compare with data

Energy Response Model

Energy Response Parameterization

$$f=\frac{E_{rec}}{E_{true}}(E_{true})=\boxed{\frac{E_{vis}}{E_{true}}(E_{true})}\cdot\boxed{\frac{E_{rec}}{E_{vis}}(E_{vis})}$$

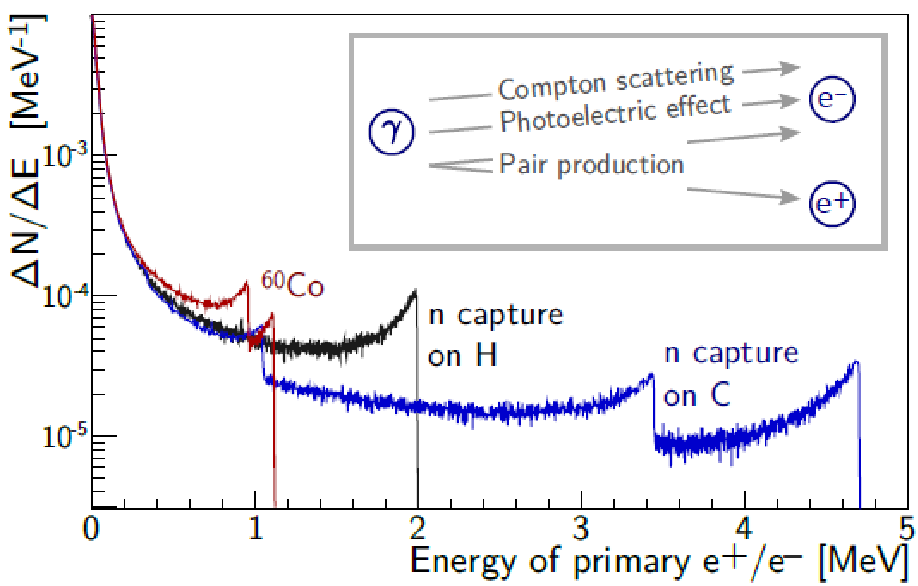
Scintillator Response

- **Electrons**
  - parameterization to model electron scintillator response

$$\frac{E_{vis}}{E_{true}}(E_{true})=\frac{1+p3\cdot E_{true}}{1+p1\cdot e^{-p2\cdot E_{true}}}$$

- **Gamma and Positron Response**
  - Gamma connected electron model through MC
  - Positron assumed to interact with the scintillator in the same way as electrons:

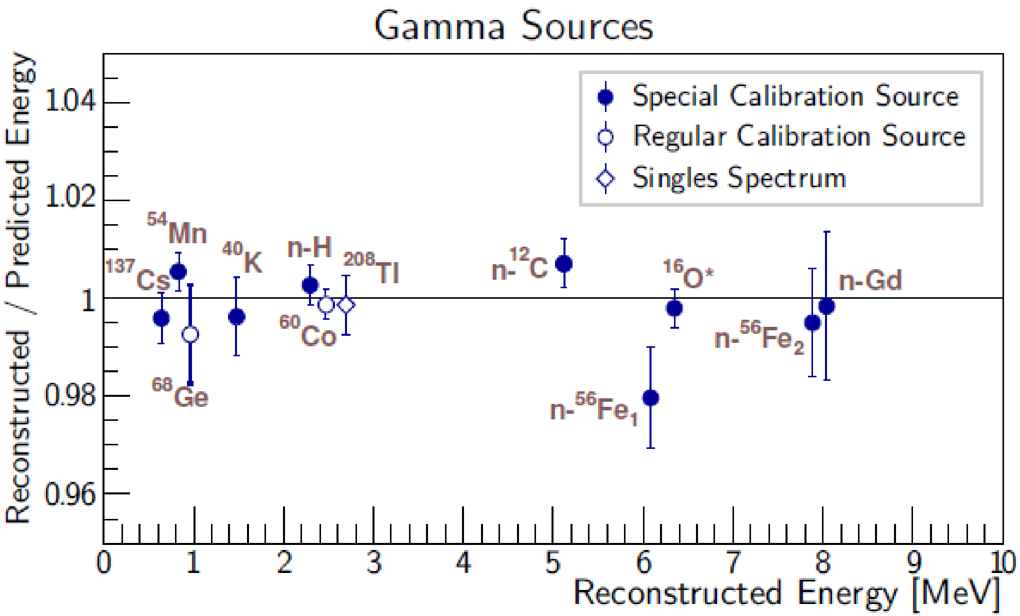
$$E_{vis}^{e+}=E_{vis}^{e-}+2\cdot E_{vis}^{\gamma}(0.511\,MeV)$$

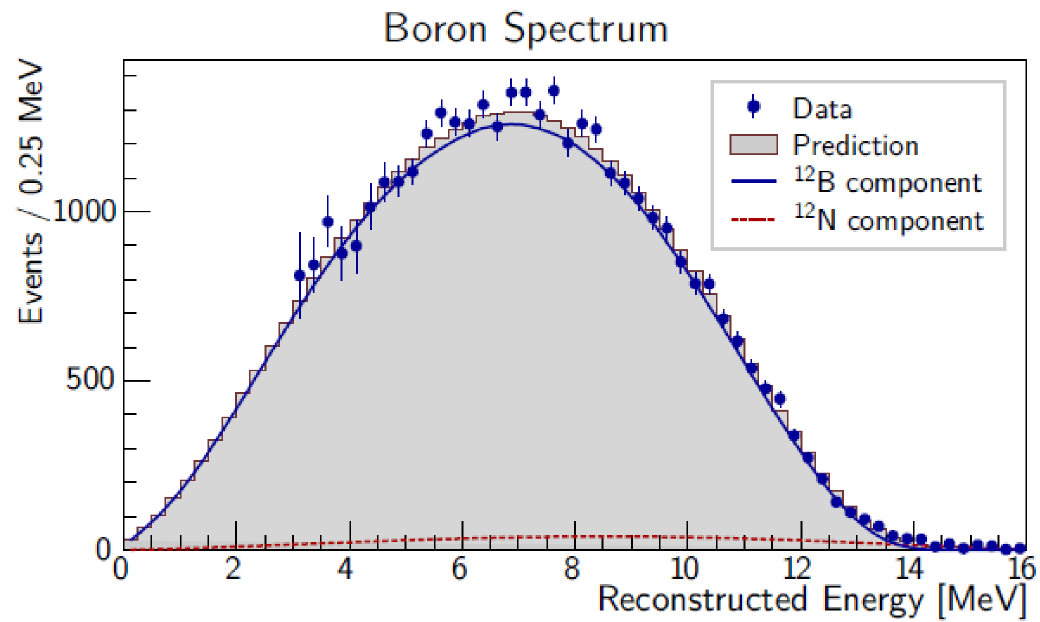


Electronics Response

- Electronics not fully capture late secondary hits
- Empirical parameterization: exponential

Energy Response Model Constrain





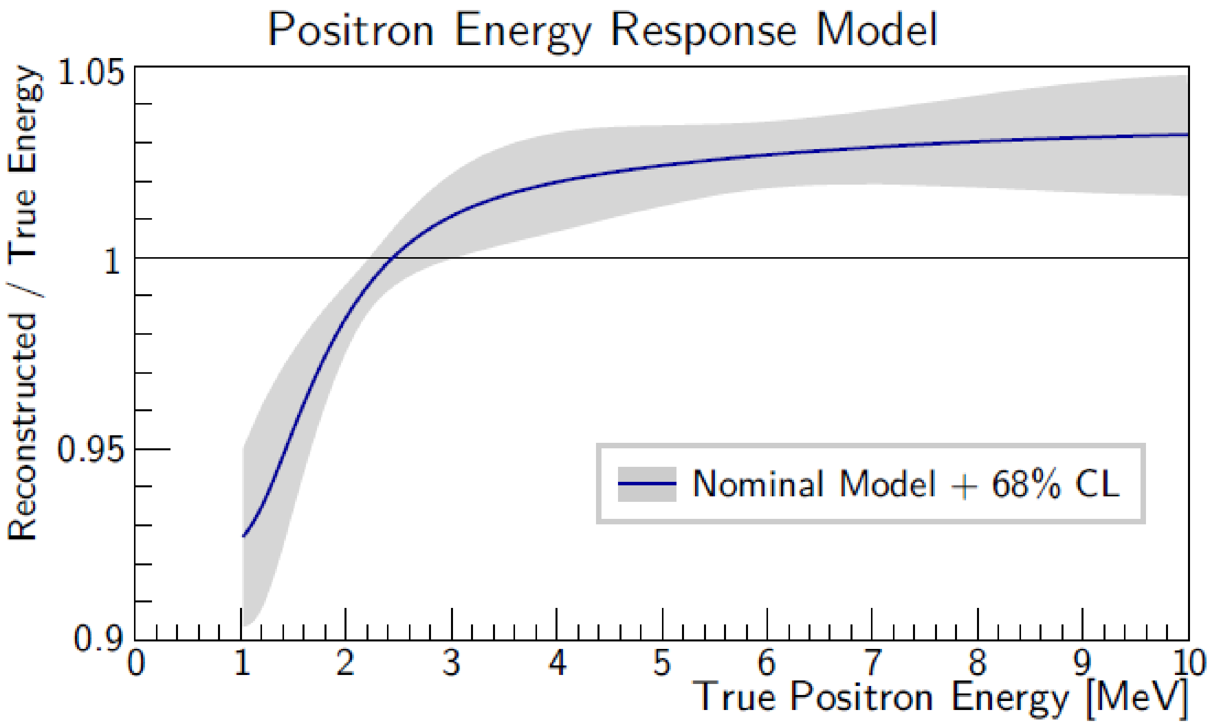
Full detector calibration data

1. Monoenergetic gamma lines from various sources
   - Radioactive calibration sources, employed regularly (^{68}Ge, ^{60}Co, ^{241}Am^{13}C) and during special calibration periods (^{137}Cs, ^{54}Mn, ^{40}K, ^{241}Am^{9}Be, Pu^{13}C)
   - Singles and correlated spectra in regular physics runs (^{40}K, ^{208}Tl, *n* capture on H)
2. Continuous spectrum from ^{12}B produced by muon spallation inside the scintillator

Standalone measurements

- Scintillator quenching measurements using neutron beams and gamma sources
- Calibration of readout electronics with flash ADC

Final Positron Energy Response

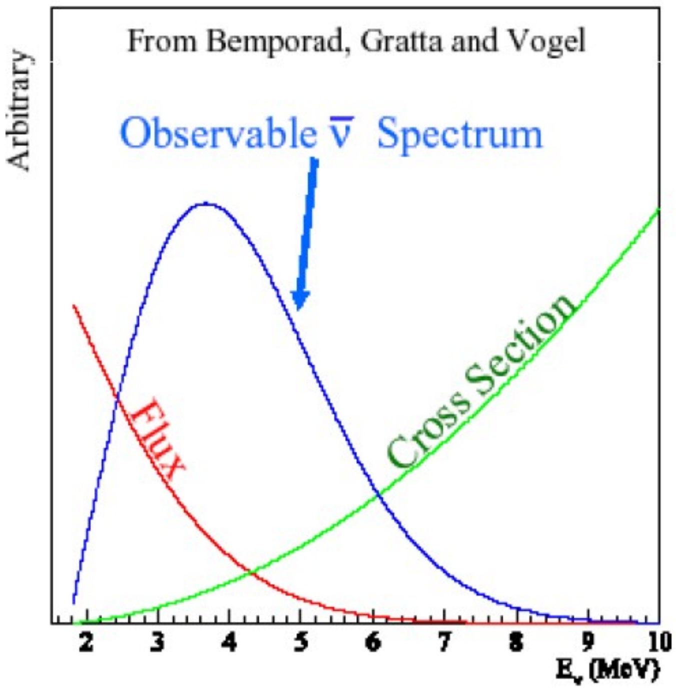


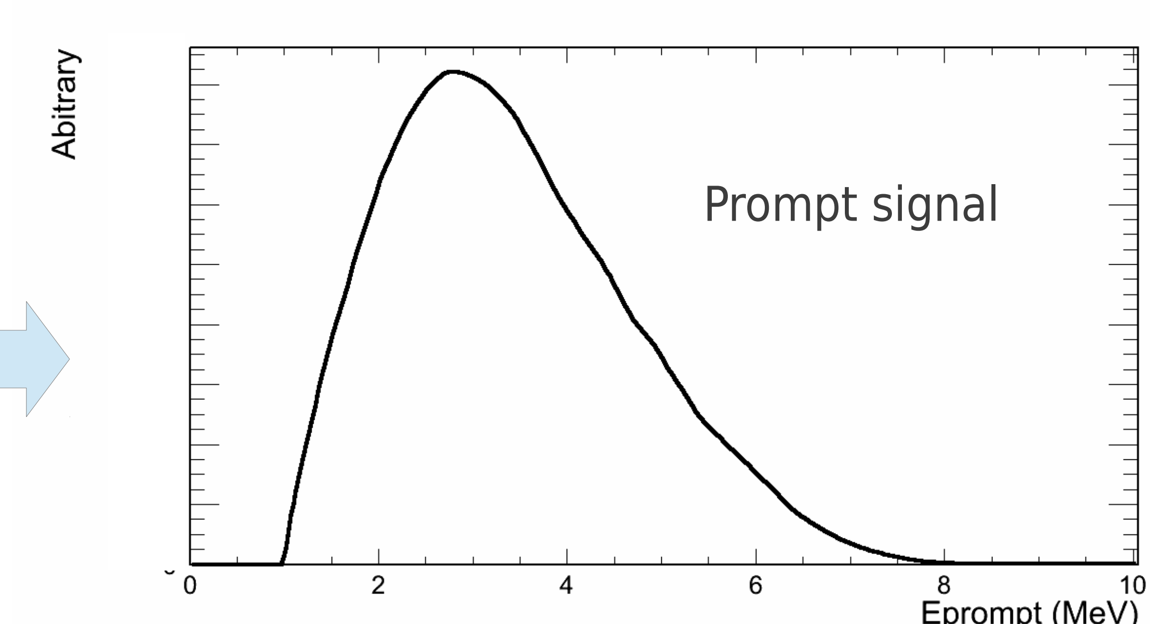
Multiple models are constructed with different parametrization and data constraints

Final Positron Energy Model:

- Conservatively combine 5 minimal correlated energy models
- All remaining models are contained in the 68% confidence interval of the resulting model
- The total positron energy response uncertainty is within 1.5%

Spectral Distortion: neutrino → positron

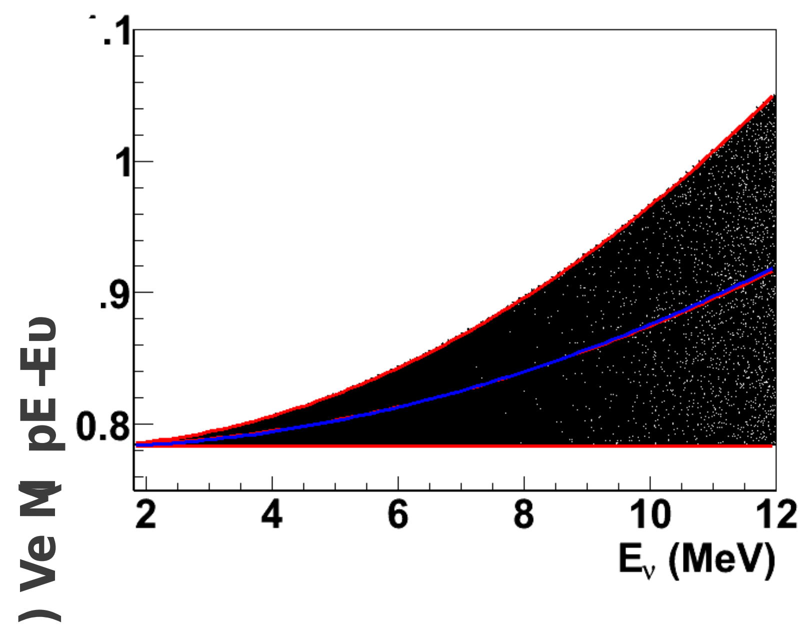




True Energy

$$\bar{\nu}_e + p = e^+ + n$$

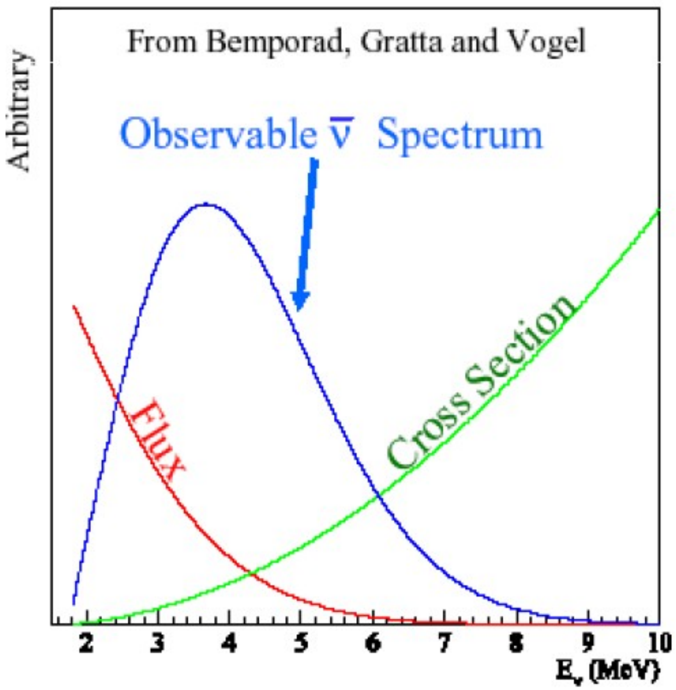
$$E_{Prompt} \simeq E_\nu - 0.78\,MeV$$

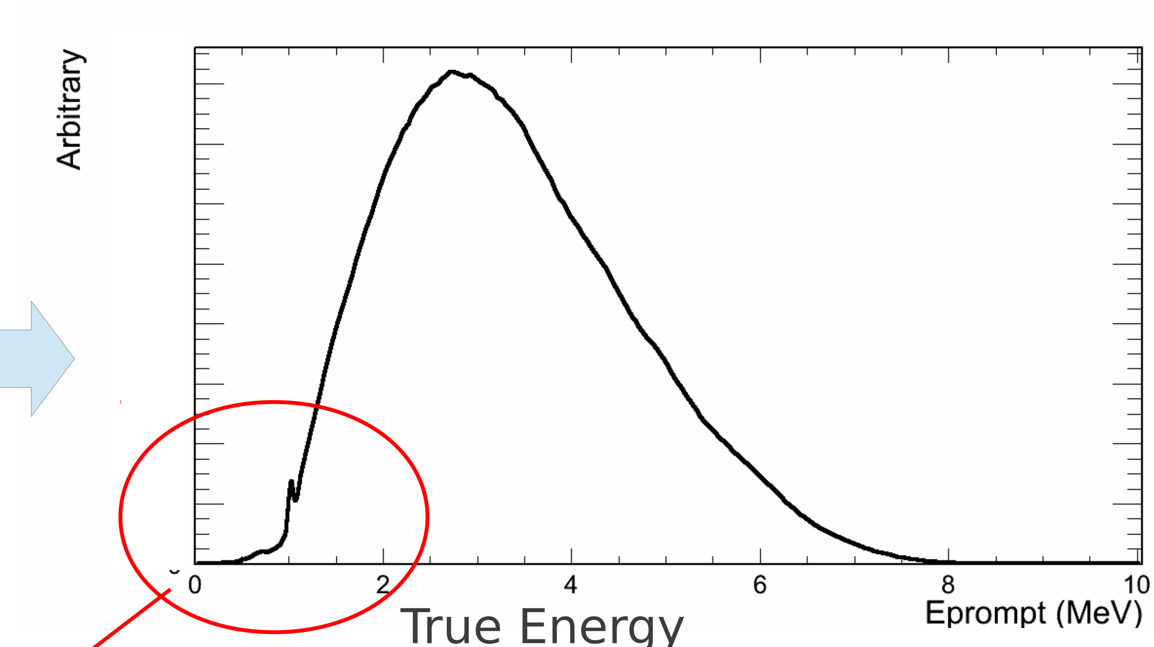


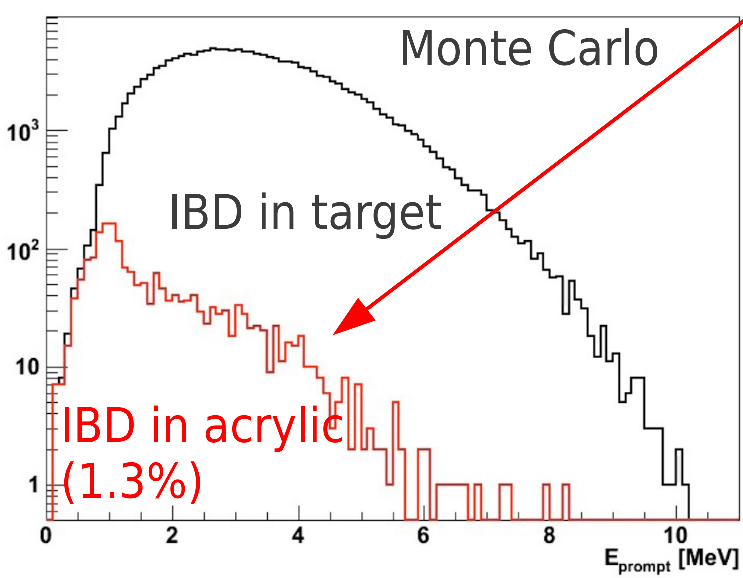
Correction with the positron angular distribution

Neglect neutron recoil energy ~10 keV

Spectral Distortion: Energy loss in Acrylic



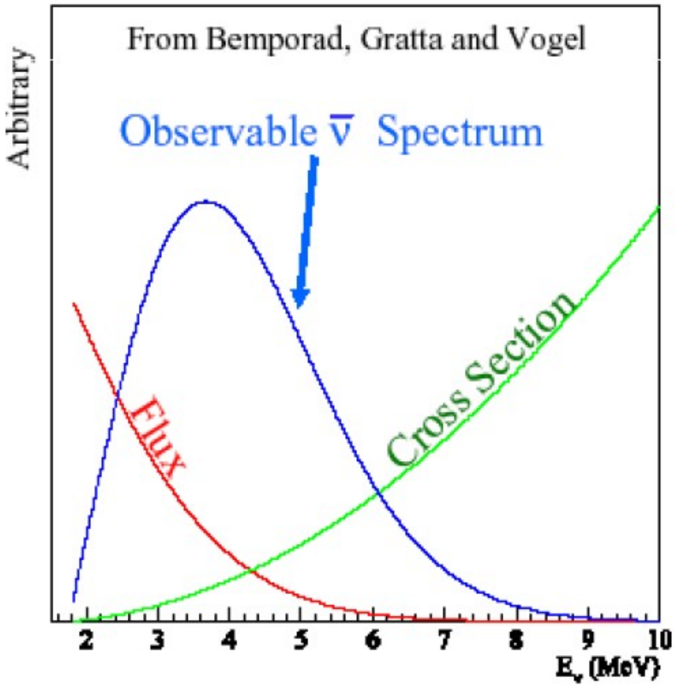


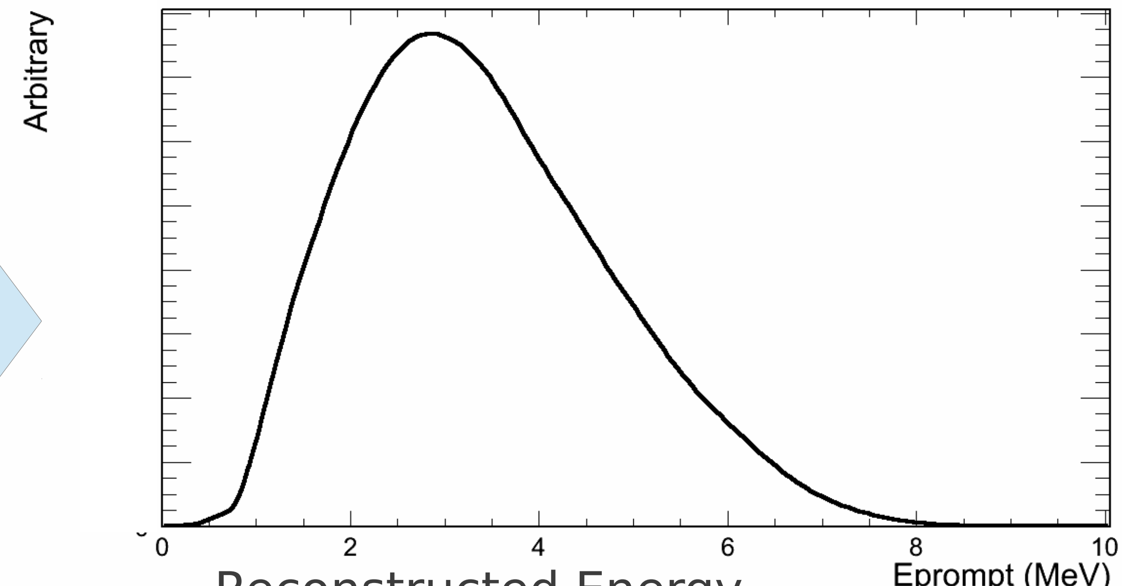


Positron energy losses in the Inner Acrylic Vessel (IAV)

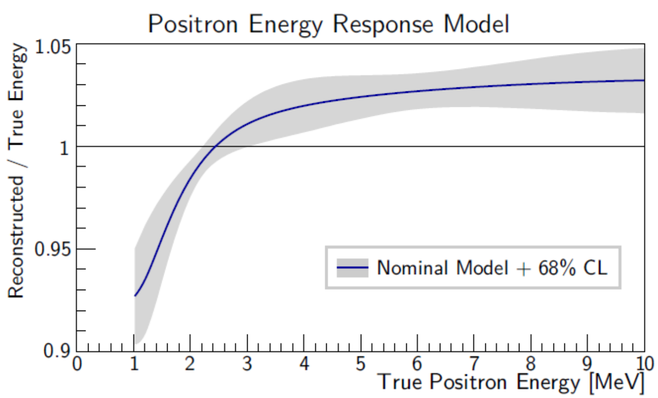
- Acrylic vessel is non-scintillating
- only 2 x 511 keV γs can be seen
- Correction based on MC

Spectral Distortion: Energy Response

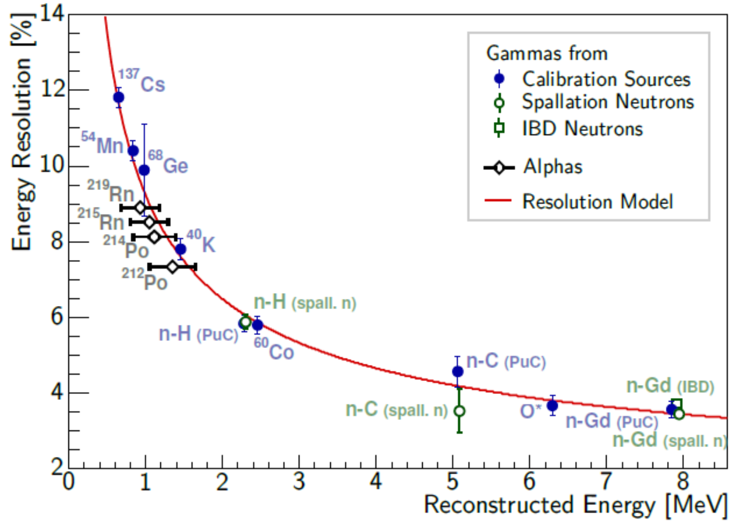




Reconstructed Energy



Energy Scale



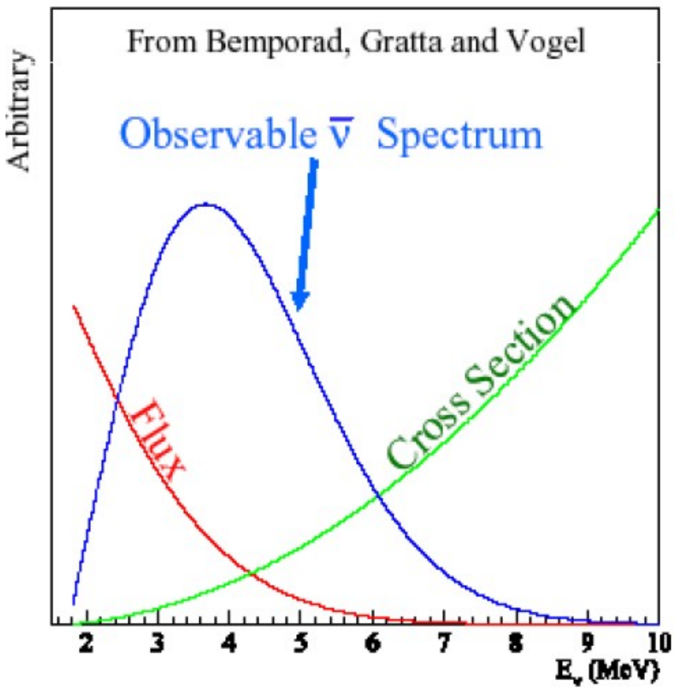
Energy Resolution

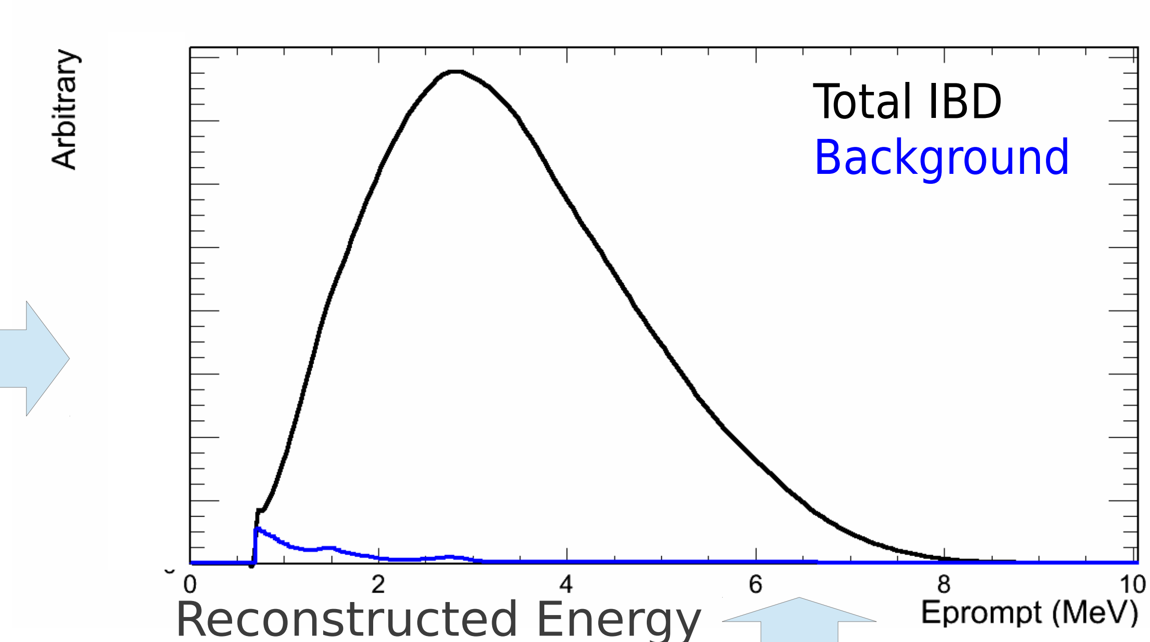
$$\frac{\sigma}{E} = \sqrt{\left(1.48\,\%^2 + \frac{8.7\,\%^2}{E} + \frac{2.71\,\%^2}{E^2}\right)}$$

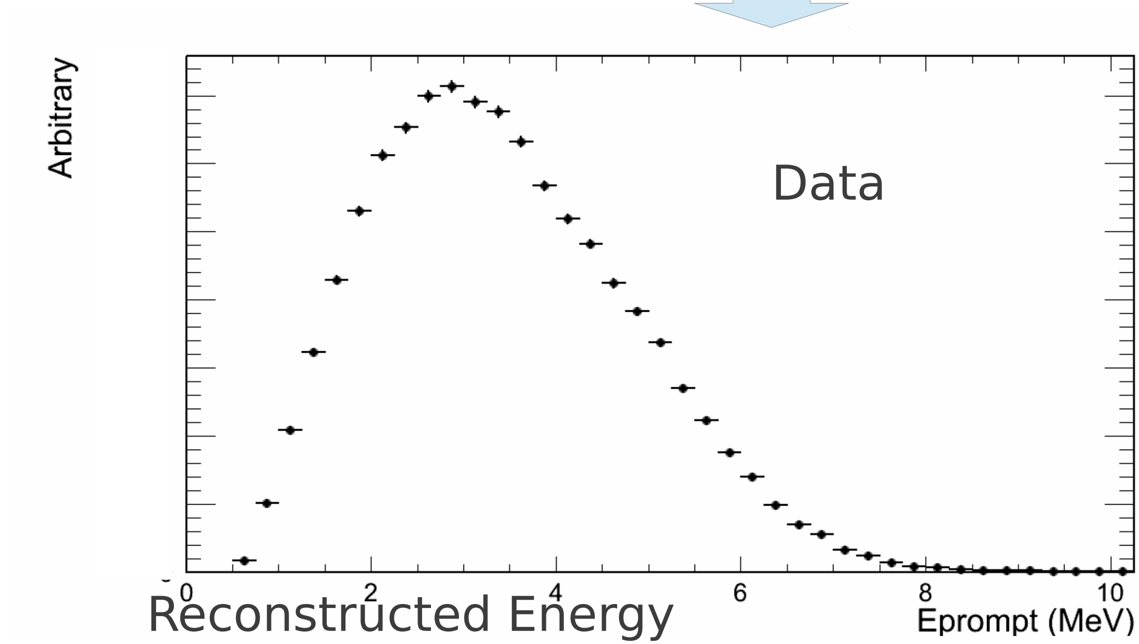
(E in the unit of MeV)

Calibrated primarily using nonmagnetic gamma sources

Spectral Distortion: Adding Background







Fit with data spectrum

χ^2 Definition

$$\chi^2 = \sum_{i}^{det\times E_p} [N_i^{pred}(\theta_{13}, \Delta m_{ee}^2, \vec{f}, \vec{\eta}, \vec{\epsilon}, \vec{b}), - N_i^{data} + N_i^{data} \log \frac{N_i^{data}}{N_i^{pred}(\theta_{13}, \Delta m_{ee}^2, \vec{f}, \vec{\eta}, \vec{\epsilon}, \vec{b})}]$$

$$+ \sum_{j}^{site\times E_p} \sum_{k}^{site\times E_p} f_j V_{jk}^{-1} f_k$$

Reactor Flux Model Constraint

$$+ \sum_{l}^{abs.E} \frac{\eta_l^2}{\sigma_l^2}$$

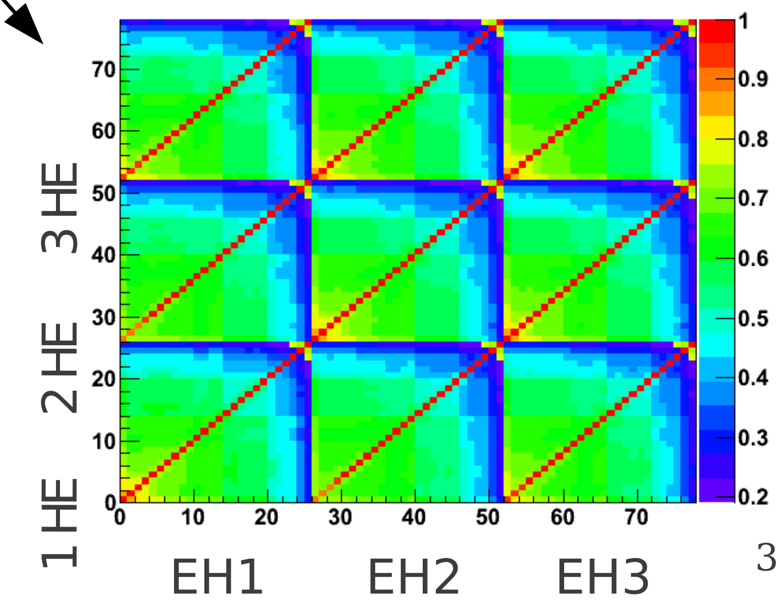
Energy Model Constraint

$$+ \sum_{m}^{det\times eff} \frac{\epsilon_m^2}{\sigma_m^2}$$

Detector Efficiency Constraint

$$+ \sum_{n}^{det\times bg} \frac{b_n^2}{\sigma_n^2}$$

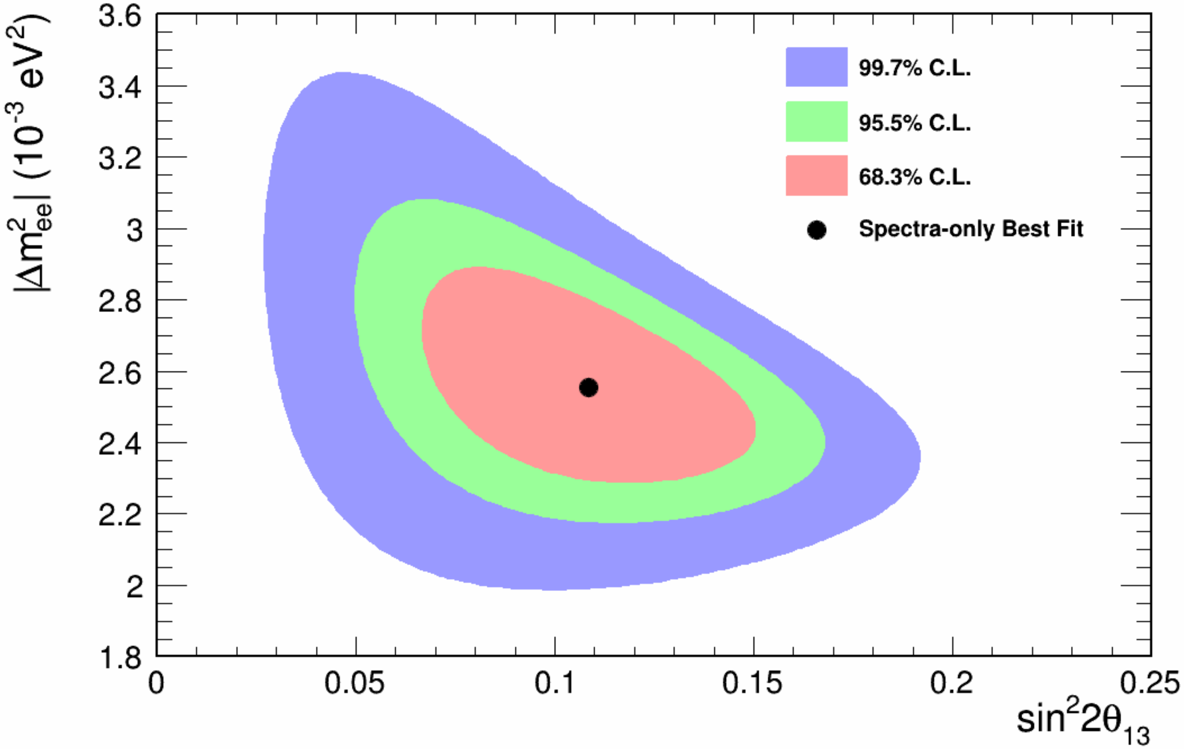
Background Constraint



- Binned maximum likelihood method
- Constrain with the uncertainty from reactor flux model, background and relative detection efficiency.
  - Using covariance matrix to reduce number of the nuisance parameters for the reactor flux model.

Far vs. near relative measurement [No constraint on the absolute rate]

Spectra Only Analysis



$$\sin^2 2\theta_{13} = 0.108 \pm 0.028$$

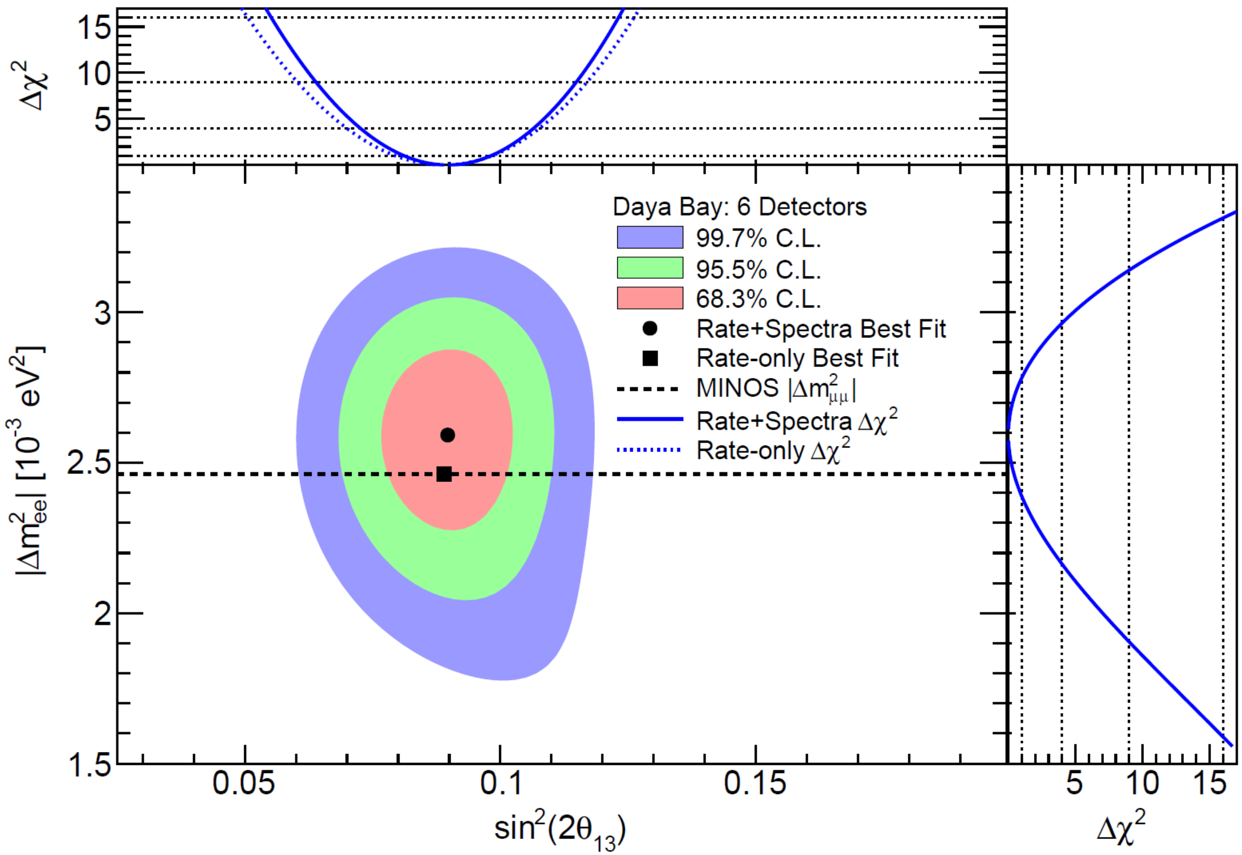
$$|\Delta m^2_{ee}| = 2.55^{+0.21}_{-0.18} \times 10^{-3} (eV^2)$$

$$\chi^2/NDF = 161.2/148$$

- **Spectra only analysis**
  - For each AD, total event prediction fixed to the observed data
    - χ^2/ NDF = 161.2/148 (Float $\sin^2 2\theta_{13}$)
    - χ^2/ NDF = 178.5/146 (Fix $\sin^2 2\theta_{13}$=0)
    - $\Delta\chi^2$/NDF = 17.3/2, corresponding to P=1.75e-4.
      - Rule out $\sin^2 2\theta_{13}$=0 at >3σ from spectra only information

Strong Confirmation of oscillation hypothesis

Rate and Spectral Analysis



$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$$

$$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3} (eV^2)$$

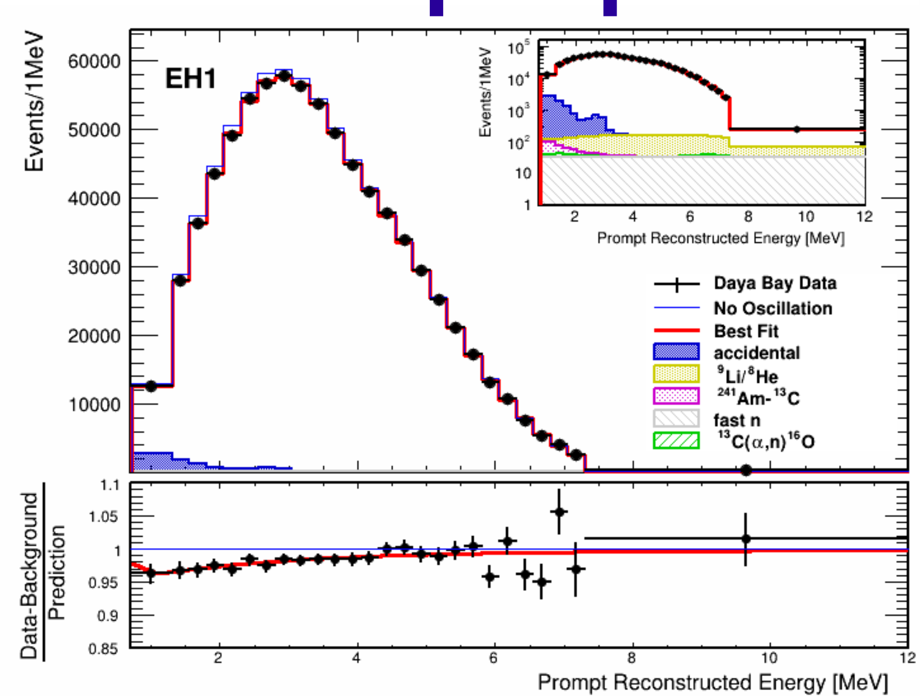
$$\chi^2/NDF = 162.7/153$$

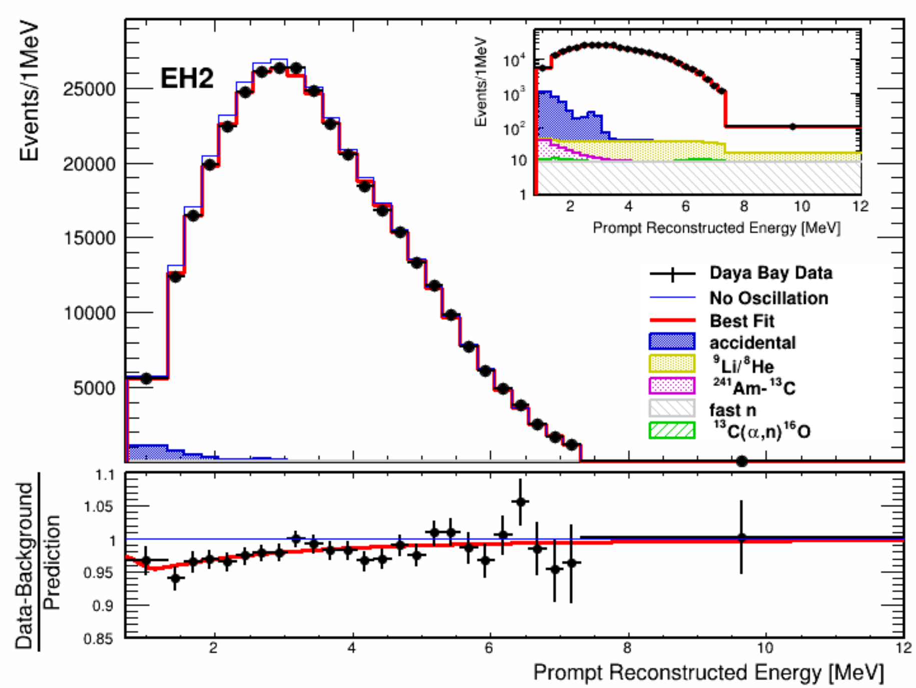
Consistent with the MINOS result

	Daya Bay	MINOS
Normal	$\Delta m^2_{32} = 2.54^{+0.19}_{-0.20} \times 10^{-3} (eV^2)$	$\Delta m^2_{32} = 2.37^{+0.09}_{-0.09} \times 10^{-3} (eV^2)$
Inverted	$\Delta m^2_{32} = -2.64^{+0.19}_{-0.20} \times 10^{-3} (eV^2)$	$\Delta m^2_{32} = -2.41^{+0.11}_{-0.09} \times 10^{-3} (eV^2)$

A.Radovic, DPF2013

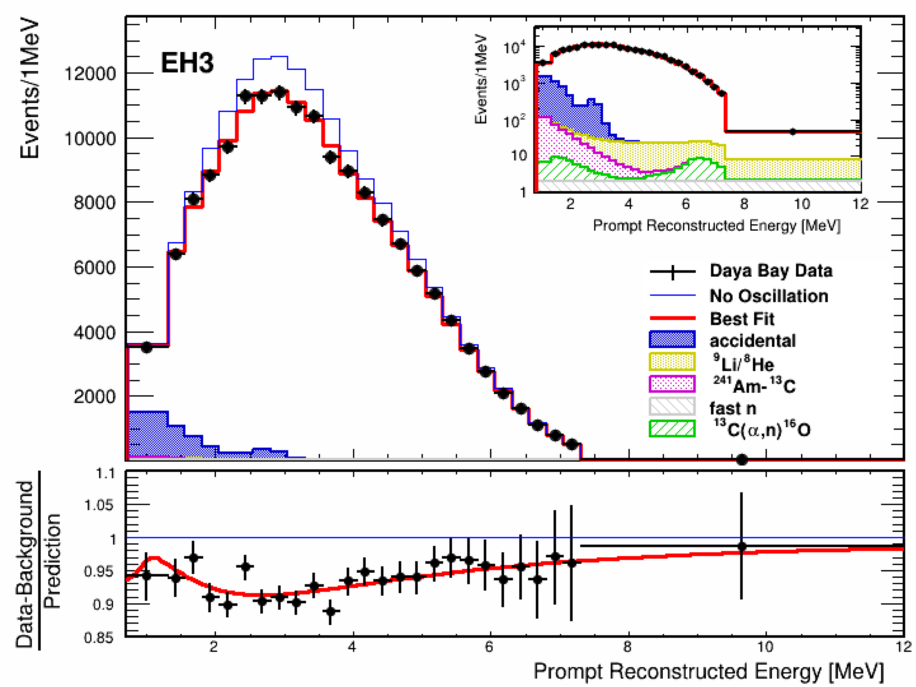
IBD Prompt Spectra



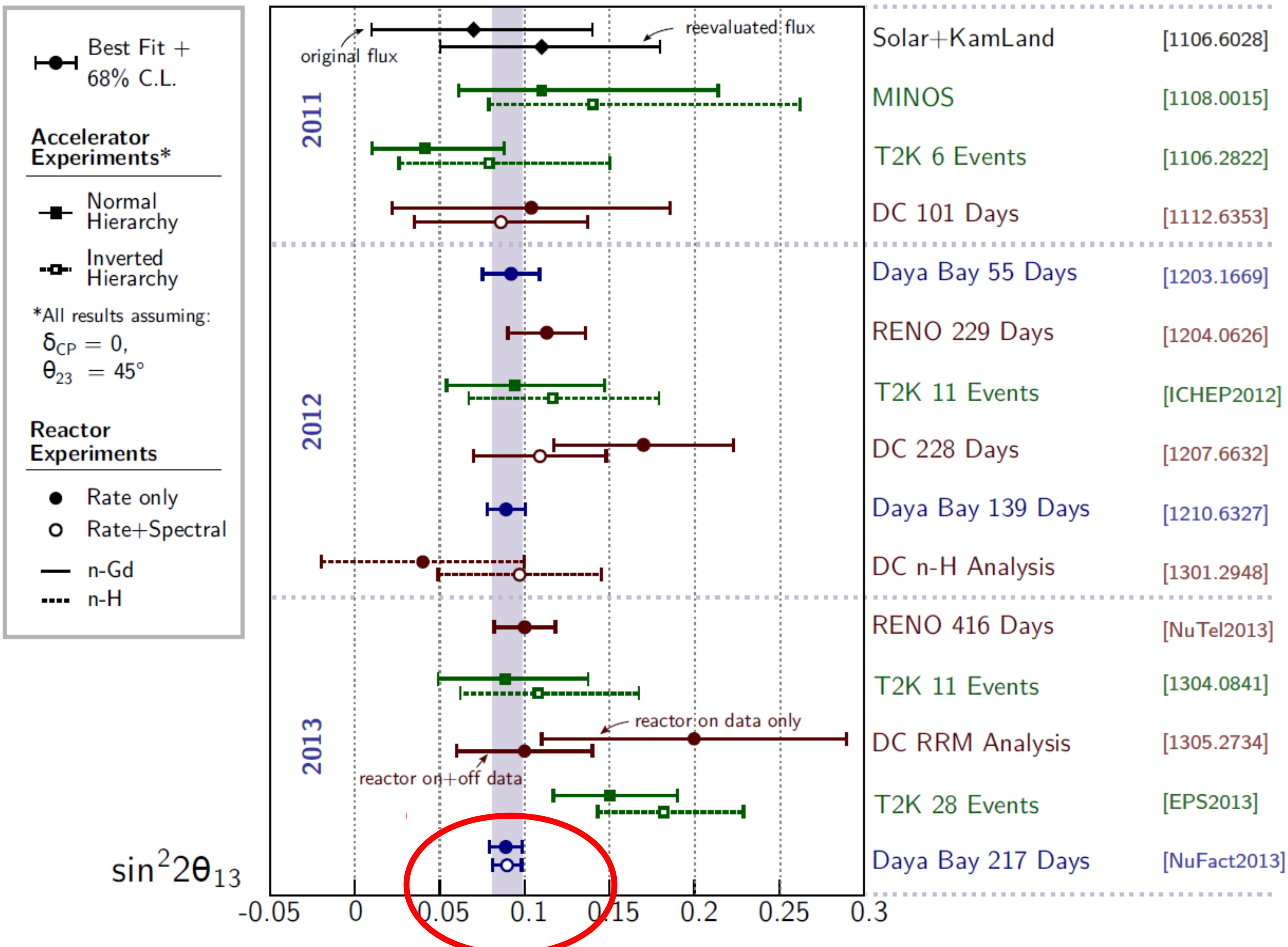


Spectrum distortion consistent with oscillation

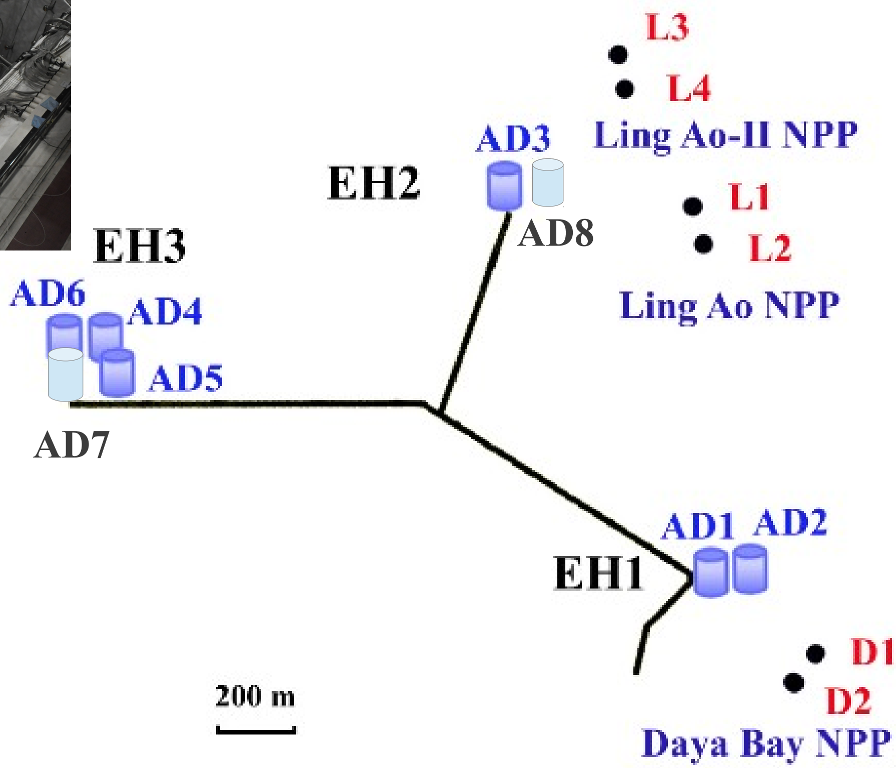
- Both background and predicted no oscillation determined by best fit
- Errors are statistical only

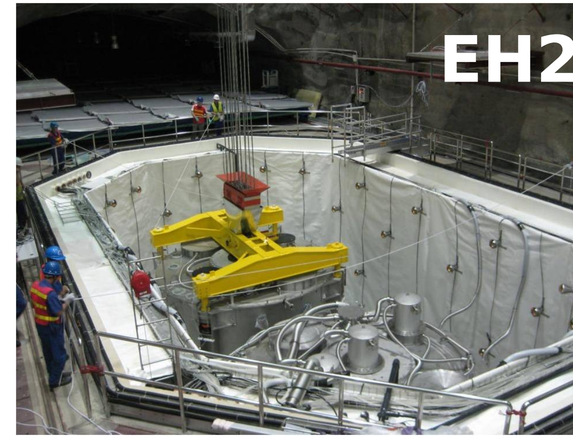


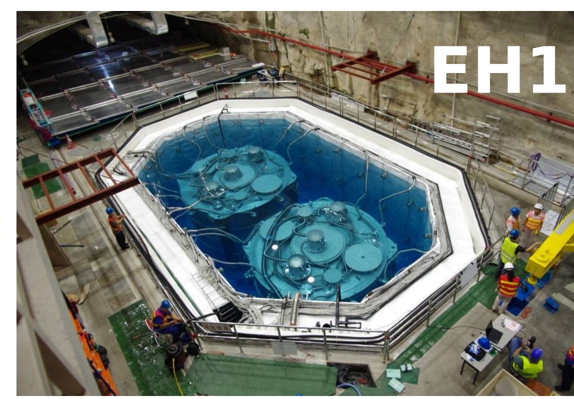
Global $\sin^2 2\theta_{13}$ results



Completion of 8-AD Installation

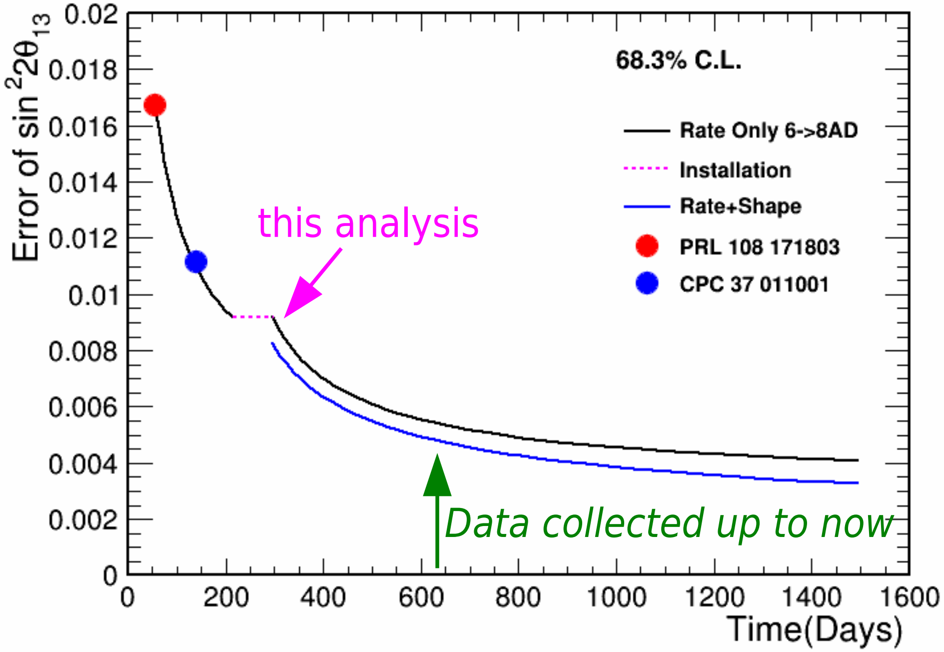


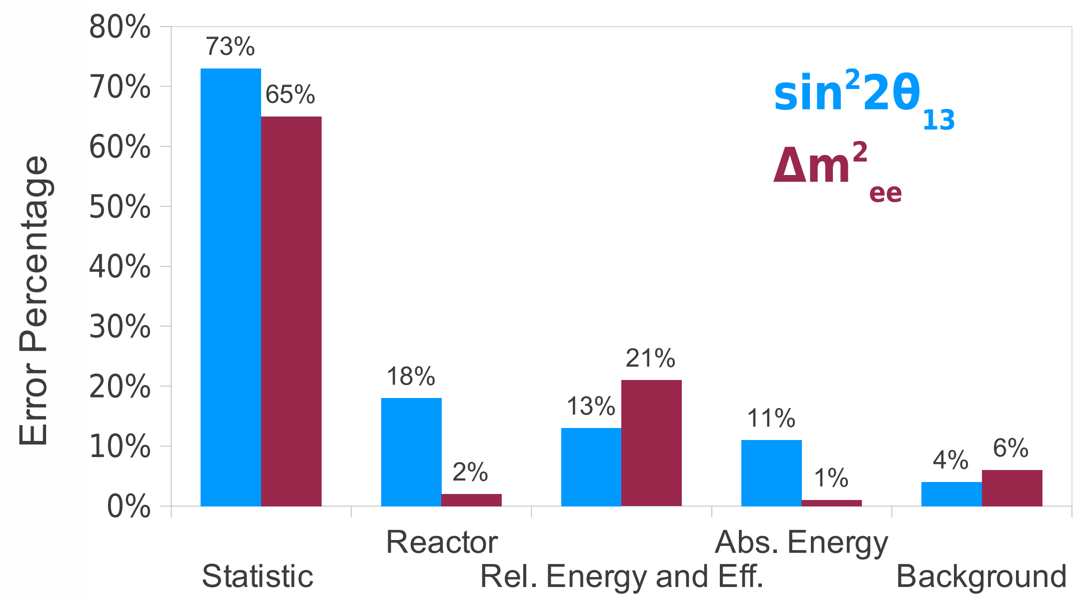




Two more ADs are installed in in EH2 and EH3 in the fall of 2012.

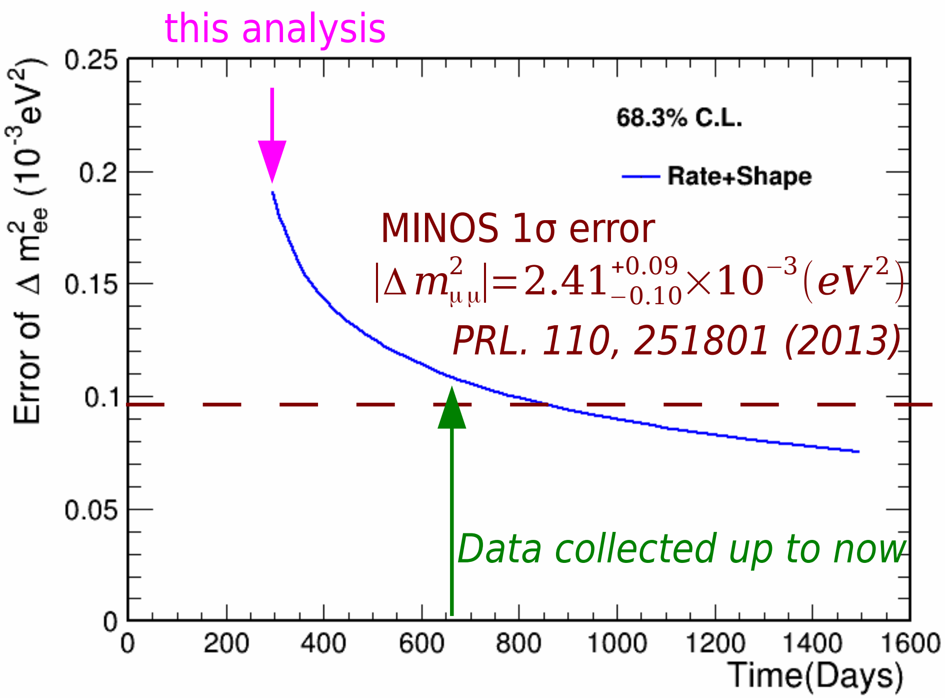
$\sin^2 2\theta_{13}$ Sensitivity Projection

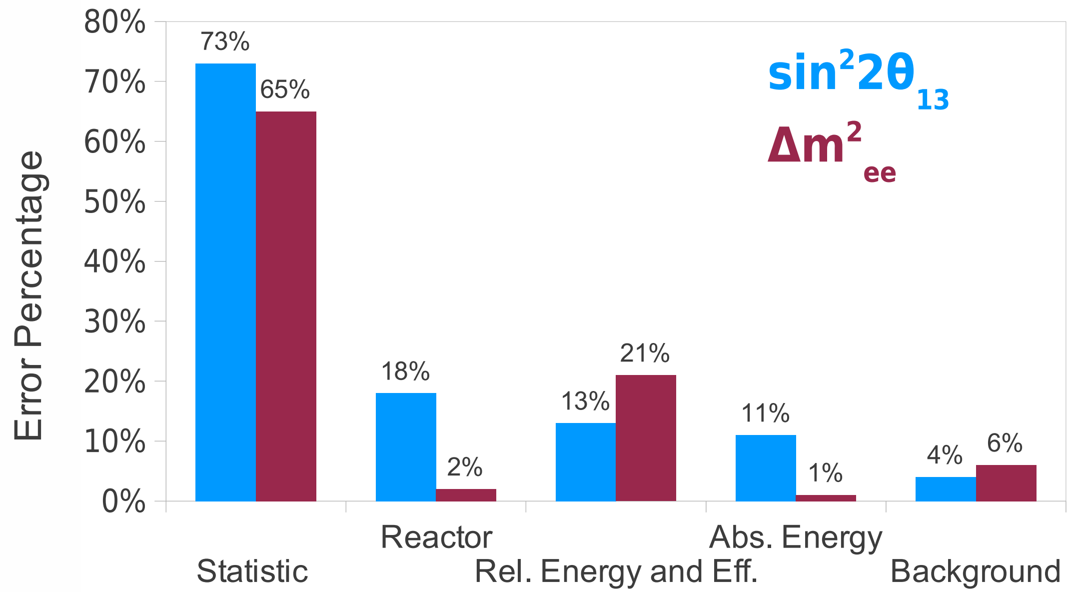




- Current errors are dominated by the statistical uncertainties (73%)
- Major systematics:
  - Reactor Model, relative+absolute energy and detector efficiency
- Daya Bay $\sin^2 2\theta_{13}$ final precision ~4%, it can be further improved by adding nH capture analysis

Δm^2_{ee} Sensitivity Projection





- Current errors are dominated by the statistical uncertainties (73%)
- Major systematics:
  - Relative energy and background
- Daya Bay $|\Delta m^2_{ee}|$ final precision ~0.1×10^{-3} eV^2, comparable to the results from μ flavor sector

Summary

- Daya Bay made the first direct measurement of the short baseline electron antineutrino oscillation frequency $|\Delta m^2_{ee}|$ and the mixing angle $\sin^2 2\theta_{13}$ from the relative deficit and spectral distortion observed based on 217 days of full 6-detector data.

$$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009} \qquad |\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3} (eV^2)$$

- Expecting from Daya Bay soon:
  - Measurement of absolute reactor flux to address the reactor anomaly
  - Significantly increase precision with 8-detector data

Neutrino physics is in a precision era!

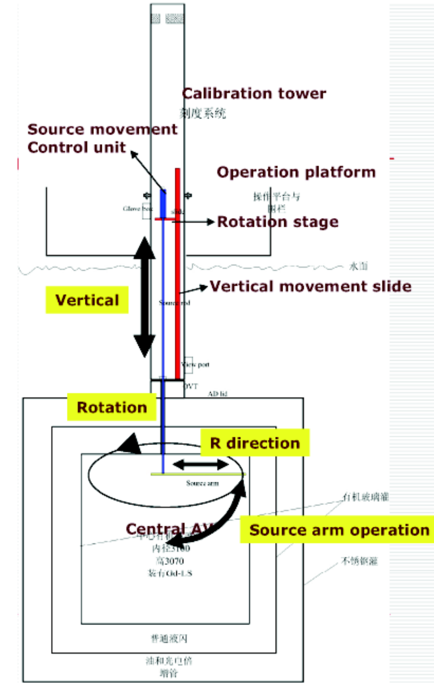
BNL Group at Daya Bay

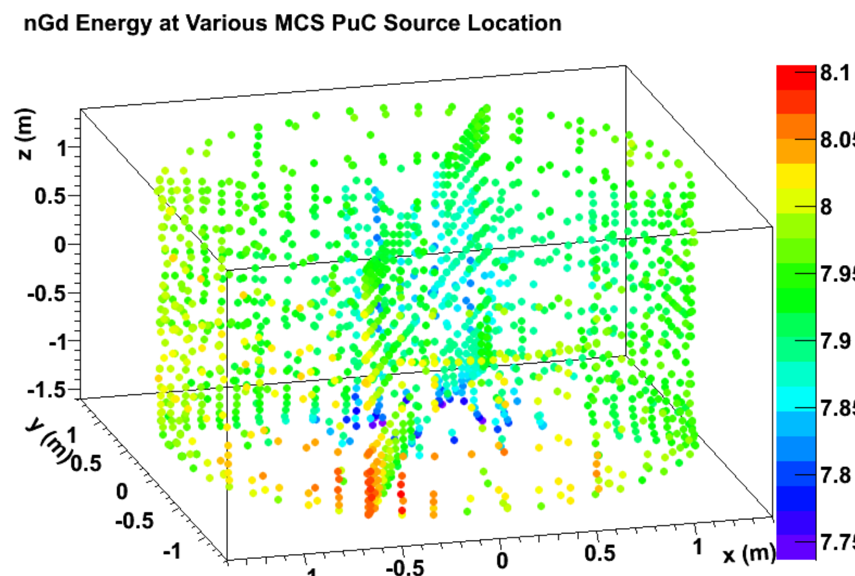
BROOKHAVEN NATIONAL LABORATORY

People missing from the picture are: Donna Barci, Wai-Ting Chan, Chellis Chasman, Zeynep Isvan, Debbie Kerr, Harry Themann, Elizabeth Worcester, Xin Qian and Minfang Yeh.

backup

Manual Calibration System (MCS)





<0.3% energy variation inside of GdLS

- MCS installed on AD1 during the summer of 2012.
- ^{239}Pu^{13}C + ^{60}Co composite source 4π source calibration, ~1700 locations

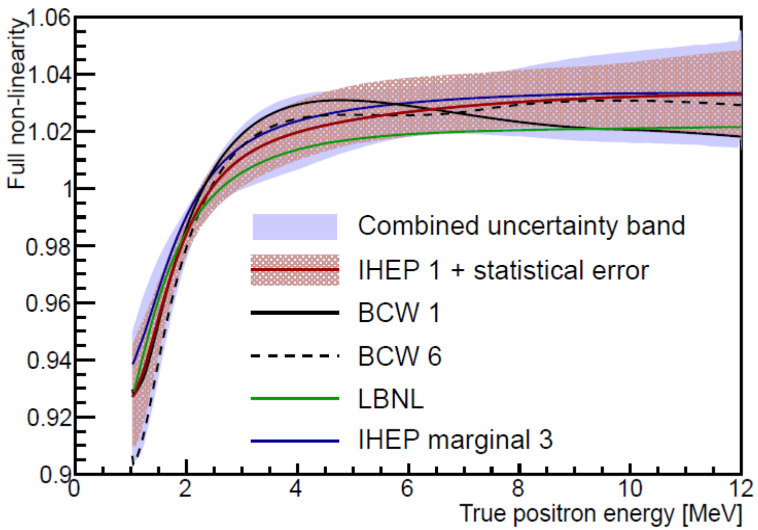
Flux Model Comparison

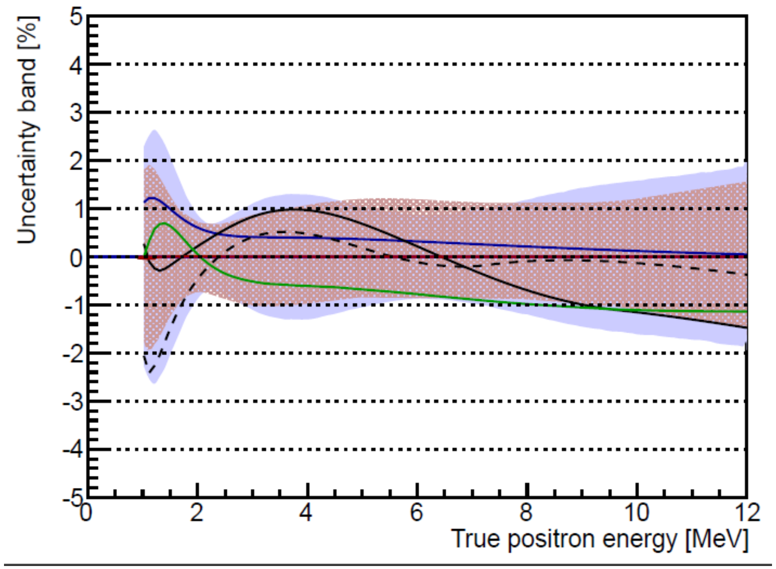
- **ILL + Petr**
  - **Rate Only:**
    - χ^2 / ndf : 0.475584 / 4
    - $\sin^2 2\theta_{13}$: 0.0890
  - **Rate + Shape:**
    - χ^2 / ndf: 162.131 / 153
    - $\sin^2 2\theta_{13}$: 0.0909
    - Δm^2_{32}: 2.48 x 10^{-3} eV^2
- **ILL + Mueller**
  - **Rate Only**
    - χ^2 / ndf : 0.479858 / 4
    - $\sin^2 2\theta_{13}$: 0.0889
  - **Rate + shape**
    - χ^2 / ndf : 163.444 / 153
    - $\sin^2 2\theta_{13}$: 0.0904
    - Δm^2_{32}: 2.51 x 10^{-3} eV^2

Site Contribution

- Site2 + Site3 (Remove Site1)
  - $\sin^2 2\theta_{13}$: 0.090 ± 0.0097
  - Δm^2_{32}: $(2.52 \pm 0.21) \times 10^{-3}\ eV^2$
- Site1 + Site3 (Removing Site2)
  - $\sin^2 2\theta_{13}$: 0.090 ± 0.010
  - Δm^2_{32}: $(2.52 \pm 0.21) \times 10^{-3}\ eV^2$
- Site1 + Site2 + Site3
  - $\mathrm{Sin}^2 2\theta_{13}$: 0.090 ± 0.0085
  - Δm^2_{32}: $(2.54 \pm 0.20) \times 10^{-3}\ eV^2$

More Nonlinearity Models...





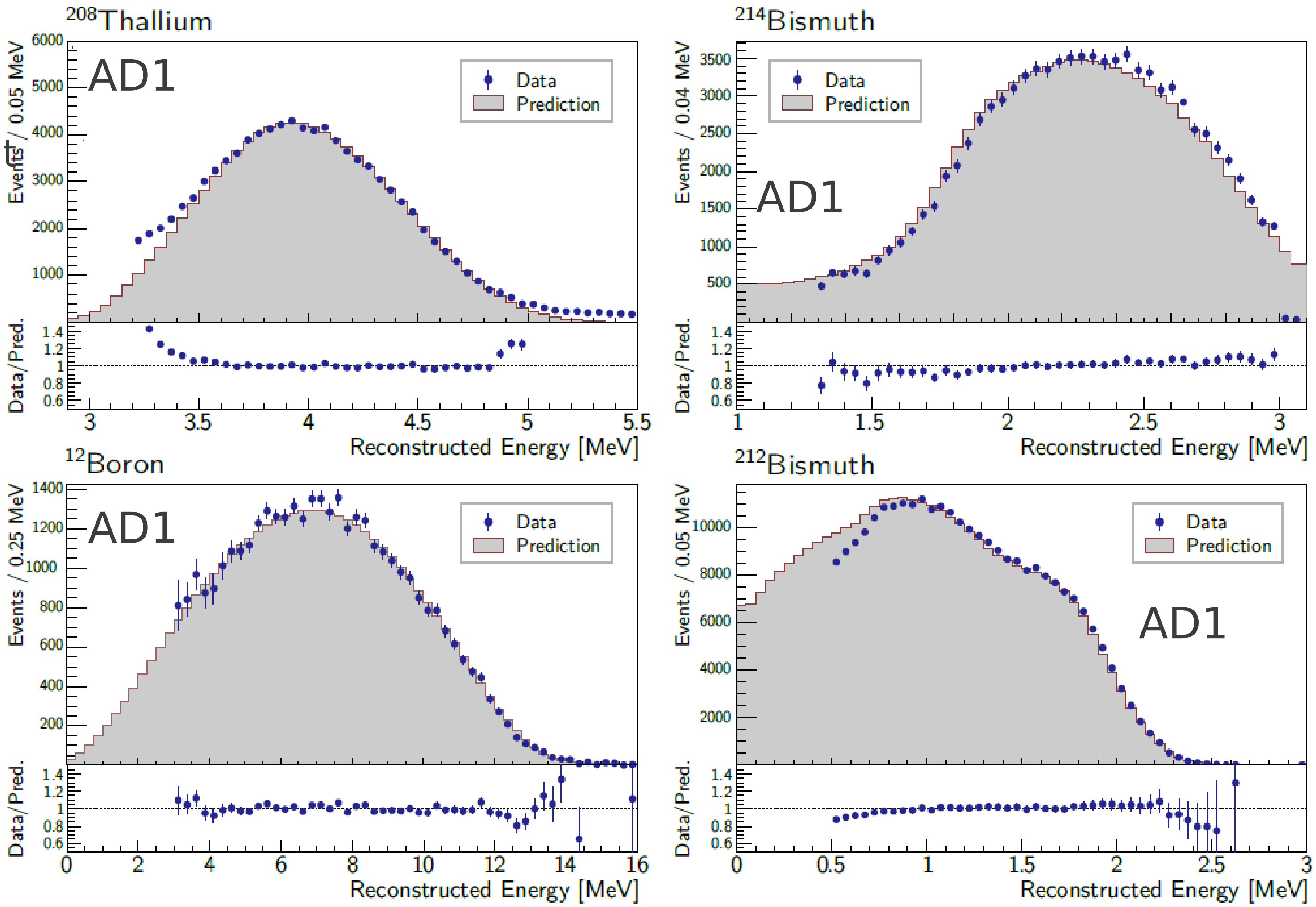
- Several other models are also built based on the different assumption of scintillator quenching, Cerenkov contribution and electronics nonlinearity. All the models agree with the beta spectra and gamma sources reasonably well.
- Combine five models conservatively to estimate the energy nonlinearity uncertainty, the total uncertainty is around 1-2%.

$$\frac{E_{rec}}{E_{true}} = \left(\frac{E_{rec}}{E_{true}}\right)_{nominal} \left(1 + \sum_{i=0}^{5} a_i (f_i - 1)\right)$$

Where $f_i = \dfrac{\left(\frac{E_{rec}}{E_{true}}\right)_i}{\left(\frac{E_{rec}}{E_{true}}\right)_{nominal}}$

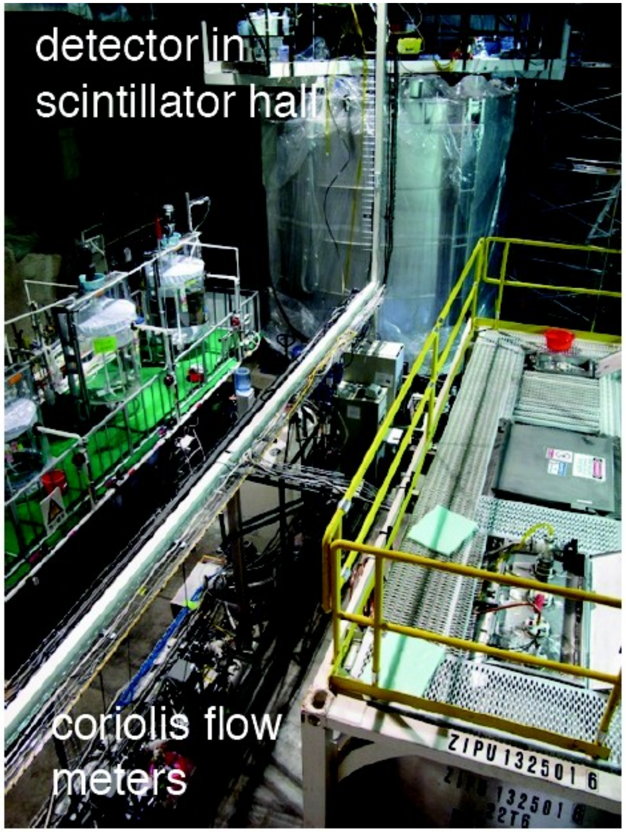
Cross Check with Continuous Spectra

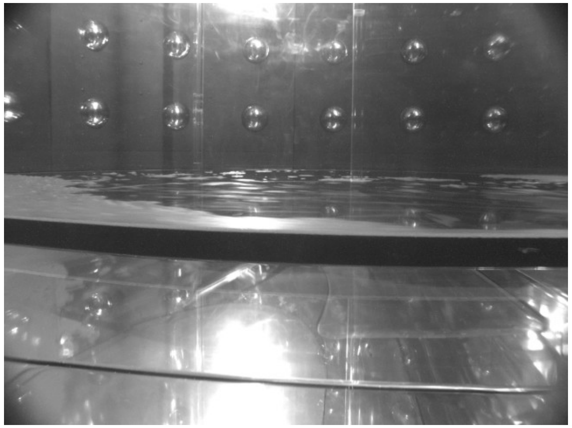
Background at low energy



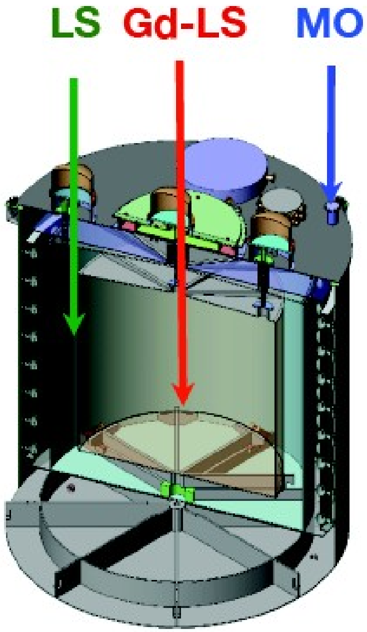
Sizable theoretical uncertainties from 1st forbidden non-unique decays.

Liquid Scintillator Filling





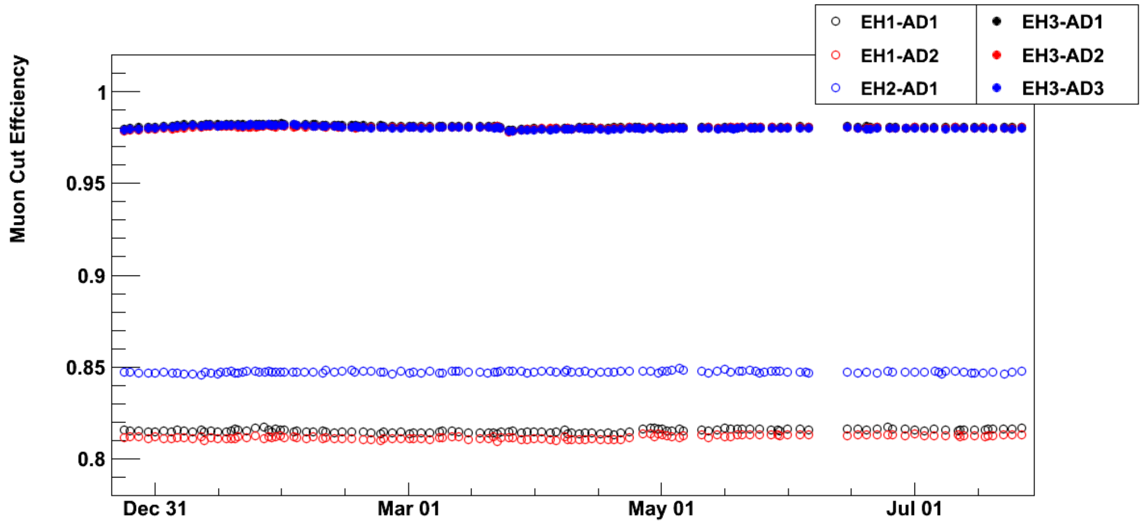
$$\frac{N_{\rm f}}{N_{\rm n}} = \left(\frac{N_{\rm p,f}}{N_{\rm p,n}}\right)\left(\frac{L_{\rm n}}{L_{\rm f}}\right)^2\left(\frac{\epsilon_{\rm f}}{\epsilon_{\rm n}}\right)\left[\frac{P_{\rm sur}(E,L_{\rm f})}{P_{\rm sur}(E,L_{\rm n})}\right]$$

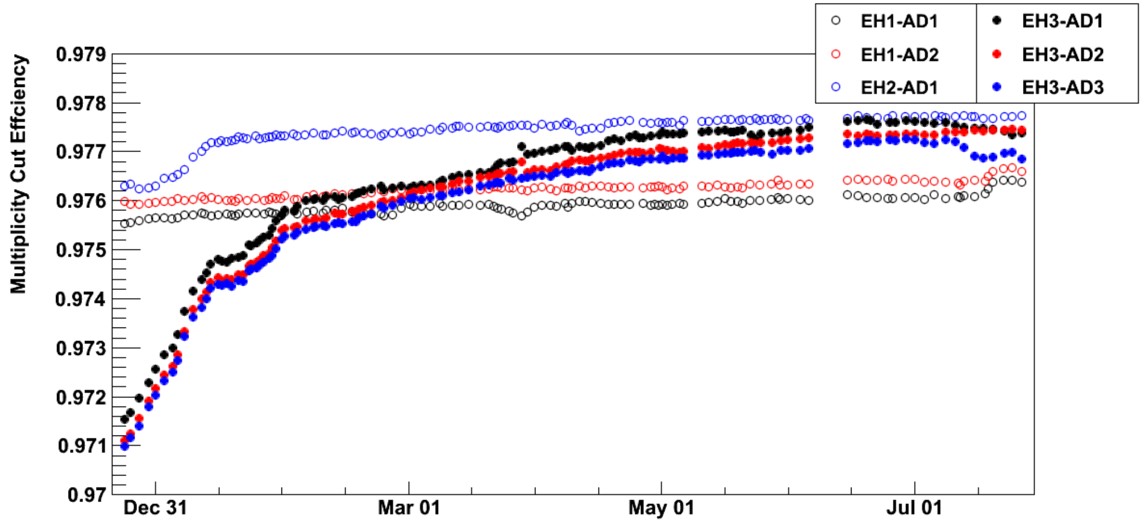


Load cells measure 20 ton target mass to 3 kg (0.015%)

- LAB + Gd (0.1%) + PPO (3 g/L) + bis-MSB (15 mg/L)
- More than 3 years R&D (BNL & IHEP)
- Multi-stage purification
- 185 ton Gd-LS + 196 ton LS production

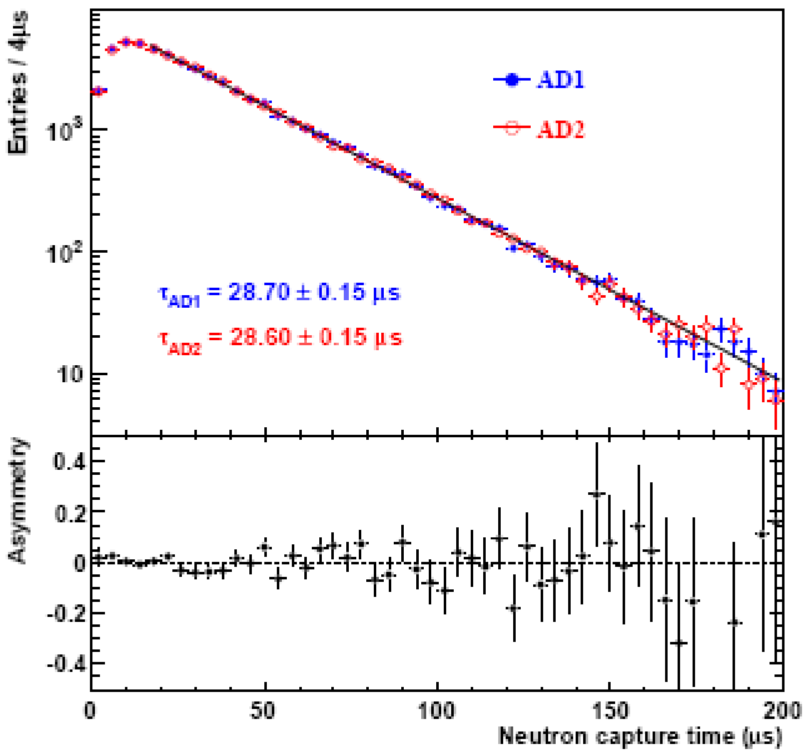
Detection Efficiency

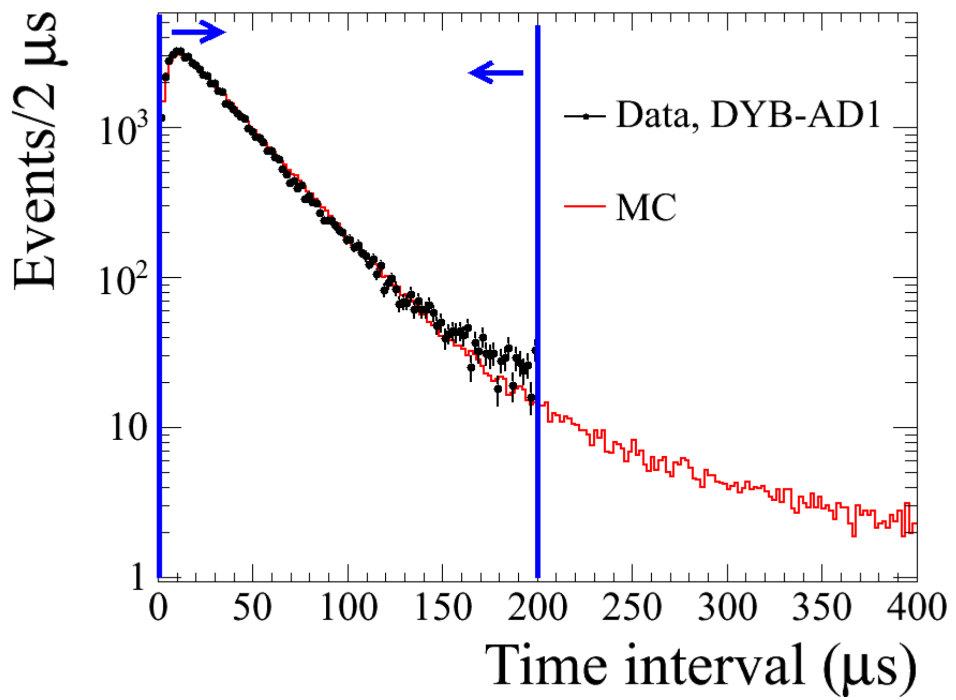




Capture Time and Gd Capture Ratio

Consistent neutron capture times in all detectors.
Capture time in each detector also constrains Gd capture ratio.





Measurement of neutron capture time from Am-C source constrains uncertainty in relative H/Gd capture efficiency to <0.1% among detectors.

Relative detector efficiency estimated within 0.01% by considering possible variations in Gd concentration.

*Data has background included, MC is pure IBD signal.

Background : β-n decay

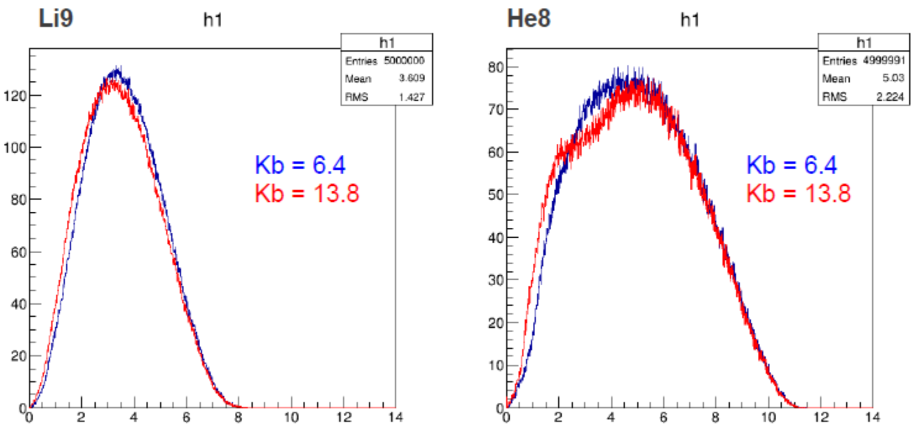
Use theoretical calculation to predict the Li9/He8 spectrum.

Due to the constrain the B12 data, we have quite good measurement of the electron quenching model.

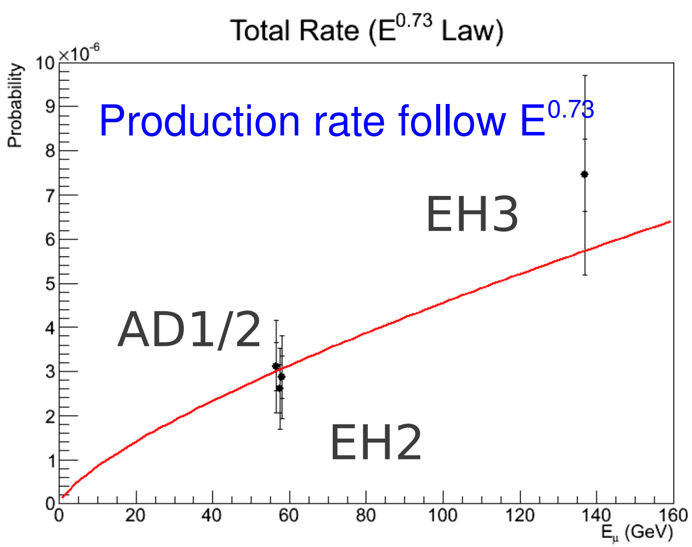
Applying the electron absolute energy scale and resolution smearing on the spectrum. The shape uncertainty is controlled by the energy nonlinearity model.

Different quenching factors applied on the neutron and alpha energy to vary to spectrum.

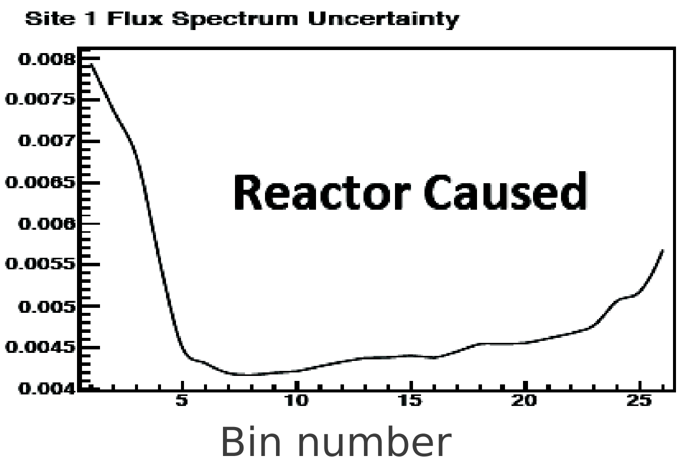
The predicted spectrum agree with measured spectrum reasonably well.

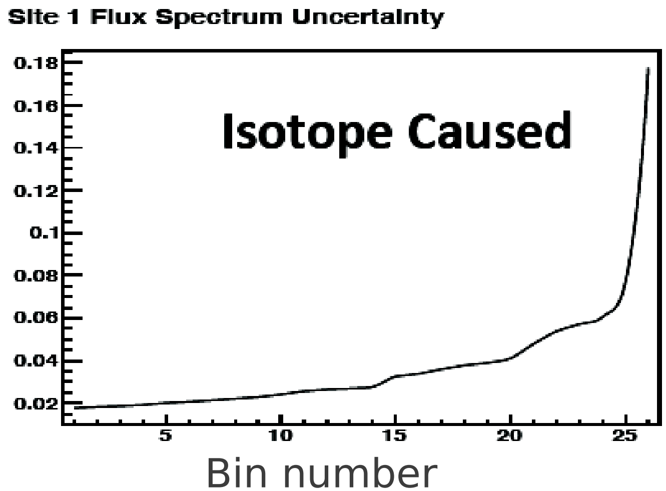


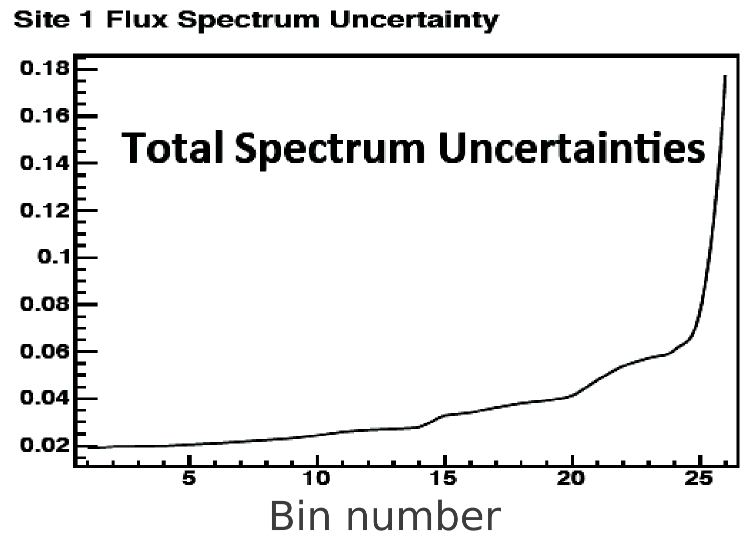
Spectrum difference due to different quenching to the neutron and alpha energy.

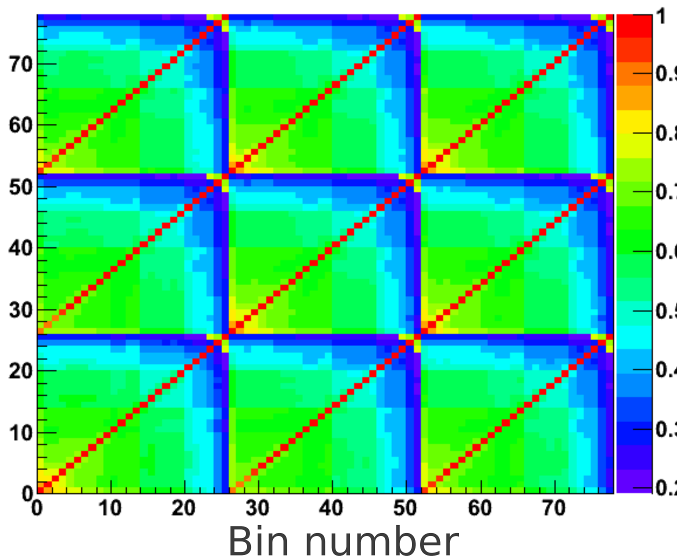


Reactor Flux Uncertainties









Construct **covariance matrix** on the detector spectrum incorporating reactor flux uncertainties, including isotope caused correlated and reactor caused uncorrelated uncertainties.

- Reducing nuisance parameters.
- Increasing fitting speed.

Additional Spectrum Correction